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The monograph presents the achievements of Ukrainian scientists on enterprise management, the use of economic and mathematical modeling, information technologies, management technologies and technical means in the field of enterprise functioning and development and project management at enterprises.

The publication is recommended for professionals in the fields of economics, information technology, project and program management – for undergraduate and graduate students, as well as academics and teachers of higher education.

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CONTENT

INTRODUCTION

The key to successful activity of complex socio-economic and technical systems is their constant updating, adaptation to the changing conditions of the external environment, and appropriate self-regulation of the internal structure, processes, and technologies. Scientific and methodological developments offered in the monograph, measures for strategic development, the use of modeling and information technologies, project and program management technologies will all contribute to the improvement of existing processes and the development of new ones. This is what determines the relevance of the studies presented.

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MATHEMATICAL MODELS OF THE CYCLIC WORK PACKAGE DISTRIBUTION TASK

Bezkorovainyi V., Bezuhla H., Cholombytko D.

The solution to the task of improving the efficiency of technologies for the distribution of work packages on the set of indicators, taking into account the workload of the executors has been obtained. The technology of distribution and execution of work as a process of functioning of three-phase multi-channel mass service system is proposed. The discipline of applications service in such a system is determined by solving the task of work distribution between the channels, and the results of modeling of its functioning cycles allow us to determine the channel occupancy by the time of distribution of the current work package. Mathematical models of single-criteria and multi-criteria tasks with target functions of financial (material), time costs and quality of work are proposed. Double-criteria tasks with different combinations of local criteria are partial variants of the multi-criteria task model. The parameters of the proposed models allow taking into account channel occupancy at the moment of distribution of the current work package and costs for their readjustment after previous work performance. In multicriteria models, it is proposed to use an accuracy-complexity effective function of utility of local criteria and universal additive-multiplicative convolution of criteria on the basis of Kolmogorov–Gabor function. The practical use of the proposed models will allow in practice to obtain the more effective solutions to the tasks of their distribution by taking into account the employment of channels and the cost of their reconfiguration after the previous work.

Introduction

The growing complexity of objects used in all areas of human activity, respectively, complicates the processes of automation of project management of their creation, modernization, re-engineering and technology management. In modern automated technologies, the methodology of the system approach is widely used, which provides for decomposition of the relevant processes into complexes of works and then individual works. The work thus separated is distributed among the executors, which are separate devices, specialists, divisions or companies.

The most large-scale example of work decomposition and distribution can be global production networks, in which the organization of production activities of multinational manufacturing or IT corporations takes place [1]. For their implementation, a methodology of work decomposition based on the results or phases of project management is used, based on the results of which project teams are formed [2–3]. Subsequently, the decomposition of separate project management tasks with the definition of executors or methods of their solution is carried out [4–6]. Depending on the peculiarities of the objects and tasks of the study, such work can be executed in parallel or with connections between them. Regardless of this, there is a need to distribute effectively the work between potential executors under the established constraints on the indicators of quality of results and resource costs [7]. The tasks of work allocation in many cases can be reduced to the classical assignment task or assignment tasks with additional requirements (scheduling of flights, construction work, production and repair work, development of software systems, etc.) [8].

In the classical assignment task, its solution is found for an equal number of works and executors only on the basis of the cost indicator:

$$\begin{cases} f(x) = \sum\limits_{i=1}^{n} \sum\limits_{j=1}^{n} a_{ij} x_{ij} \to \min, \\ a_{ij} > 0, \ i, j = \overline{1, n}, \\ \sum\limits_{i=1}^{n} x_{ij} = 1, \ j = \overline{1, n}; \ \ \sum\limits_{j=1}^{n} x_{ij} = 1, \ i = \overline{1, n}; \ x_{ij} \in \{0,1\}, \ i, j = \overline{1, n}, \end{cases} \tag{1}$$

where n is the number of works and the number of executors; a_{ij} – the time, material or financial cost of doing the i-th work by the j-th executor.

At the same time, the peculiarities of many practical tasks do not satisfy the requirements of model (1):

– because the number of works may not be equal to the number of executors, the matrices $a = \left[a_{ij} \right]$ and $x = \left[x_{ij} \right]$ are not square $\left(i = \overline{1, n}, \ j = \overline{1, m}, \ n \neq m \right)$;

– there may be prohibitions on the assignment of works;

– the goal may be to find the maximum of a target function, such as profit or quality of work $f\left(x\right) \to \max$;

– the matrix $a = \left[a_{ij} \right], \ i, j = \overline{1, n}$ may contain negative elements;

– several target functions are possible (multi-criteria assignment task).

The task in which the first four features are taken into account is called the general view assignment task. By executing preliminary transformations of the matrix $a = \left[a_{ij} \right]$, the Hungarian method can be used to solve it.

Taking into account the factors of narrow specialization of executors, different levels of their qualification and degree of workload, which are found in many practical situations, leads to the necessity of joint solution of the tasks of determining the workload of executors and distribution [9–10]. In particular, in [11–12] the dynamic task of assigning only one job with time constraints on the maximum efficiency index is considered, for which a model based on the interaction of intelligent agents is proposed. Considering this, the scientific and applied task of increasing the efficiency of work distribution technologies by developing mathematical models of cyclic distribution of work packages on a set of indicators, taking into account the workload of executors, is relevant.

Statement of the task

The object of the study are organizational, technical and organizational-technical systems designed to execute work packages. The subject of the study is the processes of distribution and execution of work packages, taking into account the resource load of the system.

This paper considers a generalized version of the task of modeling the process of executing work packages, which may arrive at random moments of time and require each of the work to execute a random amount of resources (qualification of the executor, time of execution, type of equipment, etc.). Taking into account modern approaches to modeling, such objects of research can be considered as three-phase multi-channel systems of mass service (systems with queues). The system receives applications at random points in time, any of which corresponds to a work package. The first phase channel executes distribution of works, the second phase channels execute works according to their specialization, and the third phase channel combines the results of works of the second phase channels.

A variant of the dynamic task of assigning channels to a mass service system in this formulation is considered.

Defined:

– system structure (first-phase channel, n second-phase channels functioning in parallel, each doing a separate work $j = \overline{1,n}$, and third-phase channel);

– the incoming flow of n work requests (packages), characterized by the law of distribution of intervals between them and its parameters;

– material or financial costs of executing the works of each specialization by each of the channels $c = \left[c_{ij}\right], i, j = \overline{1,n}$;

– distribution laws and their parameters for the duration of work for each specialization by each of the channels τ_{ij}, $i, j = \overline{1,n}$;

– the quality of work of each specialization by each of the channels q_{ij}, $i, j = \overline{1,n}$.

It is necessary: for a given interval of the system in the dynamics to execute cyclically the best distribution of n work among the n channels of the second phase on the indicators of financial costs $k_1 \to \min$, time spent on the execution of work $k_2 \to \min$ and quality of performance of the entire package of work $k_3 \to \max$.

To solve the task it is necessary to develop mathematical models of single-criteria and multi-criteria task of work distribution and their parametric synthesis, involving the determination of material, financial or time costs associated with the cyclic performance of work.

Mathematical models of single-criteria work distribution tasks

Let's consider the task of assigning n channels of the system to execute n work on the indicators of material or financial costs $k_1(x) \to \min$, the cost of time for work (efficiency) $k_2(x) \to \min$ and quality of performance of the entire package of work $k_3(x) \to \max$.

A mathematical model of the assignment task in terms of material and financial costs, taking into account the cost of transition to the current work c_{ij}^{o}, $i, j = \overline{1,n}$ can be presented in the following form:

$$\begin{cases} k_1(x) = \sum_{i=1}^{n} \sum_{j=1}^{n} \left(c_{ij}^{o} + c'_{ij} \right) x_{ij} \to \min, \\ \sum_{i=1}^{n} x_{ij} = 1,\ j = \overline{1,n};\ \ \sum_{j=1}^{n} x_{ij} = 1,\ i = \overline{1,n};\ \ x_{ij} \in \{0,1\},\ i, j = \overline{1,n}, \end{cases} \tag{2}$$

where c'_{ij} – is the nominal material or financial cost of doing the i-th work by the j-th channel of the system; $x = \left[x_{ij} \right]$, $i, j = \overline{1,n}$ – assignment matrix (Boolean variable $x_{ij} = 1$ if the i-th job is assigned to a i-th executor; $x_{ij} = 0$ – otherwise).

In contrast to the traditional task, in order to set the cost value $c_{ij} = \left(c_{ij}^{o} + c'_{ij} \right)$, $i, j = \overline{1,n}$, it is necessary to take into account what work was executed by the j-th channel in the previous cycle.

Depending on the peculiarities of the task, the values of total time of work execution, time of maximum work duration, duration of critical path activities of the project, etc. can be used as indicators of system $k_2(x)$ operability.

The target function of system operability for technology of sequential execution of a package of independent works has the form:

$$k_2(x) = \sum_{i=1}^{n} \sum_{j=1}^{n} \left(\tau_{ij}^{o} + \tau'_{ij} \right) x_{ij} \to \min, \tag{3}$$

where τ_{ij}^{o} – delay of the j-th channel to complete the preliminary work; τ'_{ij} – time of the i-th job execution by the j-th channel.

As an indicator of system efficiency for the technology of parallel execution of a package of independent works, it is proposed to choose the time of execution of the maximum duration of the work. In this case, the target function of system operability can be represented in the following form:

$$k_2(x) = \max_i \left\{ \left(\tau_{ij}^{o} + \tau'_{ij} \right) x_{ij} \right\} \to \min . \tag{4}$$

With this in mind, a mathematical model of the assignment task on the indicator of time costs can be presented in the following form:

$$\begin{cases} k_2(x) \to \min, \\ \sum_{i=1}^{n} x_{ij} = 1,\ j = \overline{1,n};\ \ \sum_{j=1}^{n} x_{ij} = 1,\ i = \overline{1,n};\ \ x_{ij} \in \{0,1\},\ i, j = \overline{1,n}. \end{cases} \tag{5}$$

In contrast to the traditional task to set the duration of the j-th channel of the i-th work, taking into account the waiting in the queue $\tau_{ij} = \left(\tau_{ij}^{o} + \tau'_{ij} \right)$, $i, j = \overline{1,n}$, it is necessary to take into account what work he executed in the previous cycle.

To assess the quality of execution of the work by the system $k_3(x) \to \max$, depending on the decision-making situation, the total or minimum value for the entire packet can be used:

$$k_3(x) = \sum_{i=1}^{n} \sum_{j=1}^{n} q_{ij} x_{ij} \to \max , \tag{6}$$

$$k_3(x) = \min_i \left\{ q_{ij} x_{ij} \right\} \to \max , \tag{7}$$

where q_{ij} quality of executing the i-th work by the j-th channel.

To assess options for the cyclic distribution of work simultaneously on the indicators of material (financial), time costs and quality of their implementation it is necessary to develop a multi-criteria task model.

Mathematical model of the multi-criteria work distribution task

In the cases when it is necessary to take into account several characteristics of variants of work distribution, as a rule, the transition to a single-objective task by convolution of the given local criteria is used. At that, the local criteria $k_l(x) \to \min(\max)$, $l = \overline{1,m}$ (where m is the number of local criteria of the task) can have different meaning, dimensionality, ranges, and directions of the desired change. To use local criteria in convolutions, their normalization is carried out. Due to the incomplete definiteness of decision-making situations for normalization the utility functions of local criteria $\xi_l(x),\ l=\overline{1,m}$ are used, which are considered as membership functions of the fuzzy set «The Best Value». One of the most effective among them in terms of the complex indicator «accuracy-complexity» is the convolution function [12]:

$$\xi_l(x)=\begin{cases}\overline{a_l}\cdot\left(\dfrac{\bar{k}_l(x)}{\bar{k}_{al}}\right)^{\alpha_{1l}}, & 0\le \bar{k}_l(x)\le \bar{k}_{al};\\[2ex] \bar{a}_l+\left(1-\overline{a_l}\right)\left(\dfrac{\overline{k_l}(x)-\bar{k}_{al}}{1-\bar{k}_{al}}\right)^{\alpha_{2l}}, & \bar{k}_{al}<\overline{k_l}(x)\le 1,\end{cases} \tag{8}$$

$$\bar{k}_l(x)=\frac{k_l(x)-k_l^{-}}{k_l^{+}-k_l^{-}},\ l=\overline{1,m}, \tag{9}$$

where $\bar{k}_{al}$, $\overline{a_l}$ – coordinates of the glue point of the function, $0\le\bar{k}_{al}\le 1$, $0\le\overline{a_l}\le 1$; α_{1l},α_{2l} – parameters that determine the appearance of the function on the initial and final segments; k_l^{+}, k_l^{-} – best and worst values of the local criterion $k_l(x)$.

Function (8) allows to realize linear and the most accurate non-linear in comparison with known functions (including *S*- and *Z*-shaped) approximation of the estimates of the local criterion values.

It is known that regardless of the direction of improvement of local criteria $k_l(x)\to\min$ or $k_l(x)\to\max$ their best values correspond to the maximum, and the worst - to the minimum value of the utility function $\xi_l(x),\ l=\overline{1,m}$ (8). Taking this into account, as well as relations (8)–(9), the mathematical model of the multicriteria task of work distribution can be represented in the following form:

$$\begin{cases}\xi_1(x)\to\max,\\ \xi_2(x)\to\max,\\ \xi_3(x)\to\max,\\ \sum\limits_{i=1}^{n}x_{ij}=1\ \ \forall j=\overline{1,n},\ \ \sum\limits_{j=1}^{n}x_{ij}=1\ \ \forall i=\overline{1,n}.\end{cases} \tag{10}$$

Among the convolutions used in practice, the additive convolution, the method of the main criterion and the so-called guaranteed result method are most commonly used [9]. For the most complete accounting of the advantages of the decision maker, it is proposed to use the additive-multiplicative convolution, which is based on the Kolmogorov–Gabor function [13]:

$$P(x)=\sum_{l=1}^{3}\lambda_j\xi_j(x)+\sum_{l=1}^{3}\sum_{i=l}^{3}\lambda_{li}\xi_l(x)\xi_i(x)+\sum_{l=1}^{3}\sum_{i=l}^{3}\sum_{j=i}^{3}\lambda_{lij}(x)\xi_l(x)\xi_i(x)\xi_j(x), \quad (11)$$

where λ_l, λ_{li}, λ_{lij} – weighting coefficients of local criteria $k_l(x)$ and their products $\lambda_l \geq 0$, $\lambda_{li} \geq 0$, $\lambda_{lij} \geq 0$, $l,i,j=\overline{1,m}$.

The task of determining the parameters of the convolution function (11) can be solved by methods of ranking, hierarchy analysis, and sequential advantages. However, due to the complexity of expert evaluation technologies, it is proposed to use the comparator identification technology to solve the task of parametric synthesis of model (11) [13–15].

Determination of the costs of transition to the current work c_{ij}^{o}, $i,j=\overline{1,n}$ and the j-th channel delay time to complete the previous work τ_{ij}^{o}, $i,j=\overline{1,n}$ in the target functions (2)–(4) can be carried out using analytical or simulation modeling tools of mass service systems [11].

Conclusions

The solution to the urgent scientific and applied task of increasing the efficiency of work distribution technologies by developing mathematical models of cyclic distribution of work packages according to a set of indicators, taking into account the workload of executers has been obtained. The technology of work distribution and performance as a process of three-phase multi-channel mass service system is proposed. The discipline of service requests in such a system is determined by solving the task of work distribution between the channels, and the results of modeling cycles of its functioning allow us to determine the employment of channels by the time of distribution of the current work package.

Mathematical models of single-criteria and multi-criteria task with target functions of financial (material), time costs and quality of work are proposed. The parameters of the proposed models allow taking into account the employment of the channels at the time of distribution of the current work package and the costs of their readjustment after the previous work. For the most complete accounting of benefits in multi-criteria solutions, it is proposed to use an effective in terms of accuracy-complexity utility function of local criteria and universal additive-multiplicative convolution of criteria based on the Kolmogorov-Gabor function.

Partial variants of the model of the tricriteria task are double-criteria tasks with different combinations of local criteria. Parametric synthesis of models of double-criteria and tricriteria tasks can be carried out with the use of expert evaluation or comparator identification technologies.

The practical use of the proposed models will make it possible in practice to obtain the more effective solutions to the task of their distribution by taking into account the employment of channels and the costs of their readjustment after the previous work. The direction for further research may be the development of effective methods for modeling the processes of work execution and their implementation in the methods of work package distribution.

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DECISION MAKING SUPPORT UNDER CONDITIONS OF INCOMPLETE CONSISTENCY OF EXPERT ADVANTAGES

Beskorovainyi V., Kolesnyk L., Russkin V.

To expand the prospects of intellectualization of design and management procedures for complex objects, a decision of an urgent scientific and applied problem of increasing the efficiency of multicriteria decision support technologies is proposed. A combined method for evaluating variants under conditions of incomplete consistency of expert advantages is proposed. To assess the importance of partial criteria it was proposed to use methods of reducing variance and penalizing inconsistency, allowing to increase the accuracy of assessments of weight coefficients of partial criteria. With low accuracy in determining the weighting coefficients to assess the effectiveness of decisions it is proposed to use a universal common utility function, which by changing one of the parameters allows to implement strategies for finding both the most effective and the most sustainable decisions. Practical use of the proposed method will allow to obtain more effective decisions to multi-criteria optimization problems by increasing the accuracy of assessment of weight coefficients of partial criteria. The direction of further research may be the development of effective decision support methods for fuzzy or interval characteristics of variants.

Introduction

Decision-making in project management, computer-aided design or control systems is usually carried out taking into account many heterogeneous indicators and constraints under conditions of incomplete definition of goals and input data. Typical examples are decision-making tasks in the development and implementation of investment projects, conducting tenders, product certification, choosing suppliers or contractors, optimization of variants for the construction of objects, etc. At the same time, the decisions made in such conditions, in particular, must be reasoned, objective, reproducible and protected from the authoritarian influence of individuals or organizations. It is known that the choice of decisions on a set of heterogeneous contradictory indicators, even for clearly defined goals and inputs, is a rather difficult problem [1–3].

The central task of this problem is to synthesize an adequate mathematical model for forming a scalar multifactor assessment of the effectiveness of decisions from the set of admissible $x \in X$. The complexity of the problem lies in the fact that a set of partial criteria is used to evaluate the decision variants $k_i(x),\ i=\overline{1,n}$ each of which has its functional meaning, dimensionality, interval, and direction of the desired change improvement. In such cases, to rank the decisions and choose the best among them on the set of admissible $D(m,\delta)$ is carried out based on the utility maximization paradigm [4]. The decision maker (DMP) carries out the ordering of a small set of variants $D(N, m_0, \delta_0)$ in the framework of the ordinalistic approach. The cardinalistic approach to problem solving involves the formation of a generalized criterion of effectiveness $J_E(c) = \sup\left\{\left|v\left(k, \overline{w}, c\right)\right| : k \in N, \overline{w} \in E\right\}$, using which the generalized evaluation and selection of the best variant is carried out:

$$x^o = \arg\max_{x \in X} P(x). \tag{1}$$

The value of the generalized criterion of effectiveness $\overline{w}$ (1) allows organizing variants by value $\forall x, y \in X$:

$$x \sim y \leftrightarrow P(x) = P(y);\ x > y \leftrightarrow P(x) > P(y);\ x \geq y \leftrightarrow P(x) \geq P(y). \tag{2}$$

In many cases, the processes of design, development planning and reengineering of complex objects involve the generation and analysis in automatic mode of super powered sets of alternative decisions, most of which are inefficient [5]. The final choice of the best decision is made by an RRO capable of analyzing a relatively small number of variants. The above leads to the need for clear coordination between automatic and expert DMP procedures (6). In addition, expert evaluations regarding the importance of individual indicators can vary significantly, and the partial criteria $k_i(x)$, $i = \overline{1, n}$, characterizing decision variants can be set not by their point values, but as fuzzy sets [7], random values distributed according to some law, or intervals in which the benefits are not set [4, 7–8]. On this basis, to extend the prospects of intellectualization of design and management procedures for complex objects, an urgent scientific and applied problem is the development of technologies to support collective decision-making under conditions of multicriteria and incomplete consistency of expert advantages.

The object of the study are processes of support for making design and management decisions in conditions of incomplete consistency of expert advantages.

The subject of the study are methods to support collective multi-criteria design and management decisions in conditions of incomplete consistency of expert advantages.

The aim of the work is to improve the effectiveness of decision support technologies by developing a combined method for evaluating variants in conditions of incomplete consistency of expert advantages.

Multi-criteria model of the collective decision-making problem

In the early stages of formalization, the decision-making task in terms of goals, means, and results is presented in such a form [4]:

$$\Phi : X \times S \to Z, \tag{3}$$

where X – set of alternatives; S – set of environmental states, characterizing the manifestation of uncertainty in the decision-making process; Z – set of consequences (results of the decision-making problem); Φ – some mapping.

In notations (3), the decision-making process consists in choosing a subset of alternatives from the set X according to some principle of optimality P (2), and the decision-making problem is to choose alternatives $x \in X$, which leads to some result $z \in Z$ under the state of the environment $s \in S$ [4].

Efficiency of problem decision $x \in X$ is determined by the degree of correspondence of the obtained result $z \in Z$ to the set goals, evaluated by values of the set of chosen partial criteria $k_i(x)$, $i = \overline{1,n}.$, quantitative characteristic of efficiency of each alternative $x \in X$ is utility function $P(x)$, depending on values of which the choice of decision $x^o \in X$ is made (1). The process of choice $x^o \in X$ is called a decision-making procedure, and the result of choice x^o is the best (optimal, effective) decision.

The problem of collective decision-making is considered in this formulation. Given: a set of alternatives $X = \{x\}$, each of which is characterized by a set of partial criteria $\{k_i(x)\}$, $i = \overline{1,n}.$ It is necessary to determine the best alternative from the set of admissible $x^o \in X$, if the significance of partial criteria $\lambda = [\lambda_i]$, $\sum_{i=1}^{n} \lambda_i = 1$, $\lambda_i \geq 0$, $i = \overline{1,n}$, determined by a group of experts, and the estimates of each of the experts $\lambda' = \left[\lambda_i'^{\,j}\right]$, $j = \overline{1,m}$ significantly different.

The most common for assessing the generalized utility of decision variants $P(x)$ is an additive function of the type:

$$P(x) = \sum_{i=1}^{n} \lambda_i \xi_i(x), \tag{4}$$

where $\xi_i(x)$ – value of the partial criterion utility function $k_i(x), 0 \leq \xi_i(x) \leq 1$, $i = \overline{1,n}$ for the decision x.

The minimum number of machine operations to calculate their values among the common requires a partial criterion utility function with a parameter value $\alpha_i = 1$ [4]:

$$\xi_i(x) = \left\{\left[k_i(x) - k_i^-\right] \Big/ \left[k_i^+ - k_i^-\right]\right\}^{\alpha_i}, \quad i = \overline{1,n}, \tag{5}$$

where $k_i(x)$, k_i^+, k_i^- – the value of the i-th partial criterion for the decision x, its best and worst value.

Function (5) is monotonous and dimensionless, has a single interval of variation from 0 to 1, is invariant to the form of extremum of partial criterion, allows to realize both linear and non-linear (convex upward and downward) dependence on values of partial criterion. For more precise *S*- and *Z*- like approximation of the estimates of the partial criteria values is proposed to use a universal glue function, which is the best in terms of the complex indicator «accuracy-complexity» [9–10]:

$$\xi(x) = \begin{cases} \bar{a}(b_1+1)\left(1-\left(b_1 \Big/ \left(b_1 + \dfrac{\bar{k}(x)}{\bar{k}_a}\right)\right)\right), 0 \le \bar{k}(x) \le \bar{k}_a; \\ \bar{a} + (1-\bar{a})(b_2+1) \times \left(1-\left(b_2 \Big/ \left(b_2 + \dfrac{\bar{k}(x) - \bar{k}_a}{1-\bar{k}_a}\right)\right)\right), \bar{k}_a < \bar{k}(x) \le 1, \end{cases} \tag{6}$$

where $\bar{k}(x)$ – the value of the partial criteria utility function (5) for $\alpha_i = 1$; $\bar{k}_a, \bar{a}$ – normalized coordinate values of the glue point of the function, $0 \le \bar{k}_a \le 1$, $0 \le \bar{a} \le 1$; b_1, b_2 – parameters that determine the type of dependence on the initial and final segments of the function.

The most adequate for assessing the generalized utility of decision variants $P(x)$ is a function based on the Kolmogorov–Gabor polynomial [4–6]:

$$P(x) = \sum_{i=1}^{n} \lambda_i \xi_i(x) + \sum_{i=1}^{n}\sum_{j=i}^{n} \lambda_{ij}\xi_i(x)\xi_j(x) + \sum_{i=1}^{n}\sum_{j=i}^{n}\sum_{l=j}^{n} \lambda_{ijl}\xi_i(x)\xi_j(x)\xi_l(x) + \ldots, \tag{7}$$

where λ_i, λ_{ij}, λ_{ijl} – coefficients of importance of the criteria $k_i(s)$, $i = \overline{1,n}$ and criterion products $k_i(x)$, $k_j(x)$, $k_l(x)$.

The generalized utility function (4) is a special case of function (7). By entering a set of notations $\lambda_{1,2} = \lambda_{n+1}$, $\lambda_{1,3} = \lambda_{n+2}, \ldots$, $\xi_1(x)\xi_2(x) = \xi_{n+1}(x)$, $\xi_1(x)\xi_3(x) = \xi_{n+2}(x), \ldots$ function (7) can be represented in the form (4) at $n = N$ (where N – total number of addends in the function (7)).

In the technologies of collective decision-making to solve the problem (1) using models (4) – (7) it is necessary to set estimates of weight coefficients of partial criteria $\lambda=[\lambda_i]$, $i=\overline{1,n}$ based on contradictory expert opinions $\lambda'=\left[\lambda_i'^{\,j}\right]$, $j=\overline{1,m}$ (where $\lambda_i'^{\,j}$ – the significance of the i-th partial criterion is determined by the j-th expert; m – the number of experts).

Parametric synthesis of a collective decision-making model

If the estimates of the experts $\lambda'=\left[\lambda_i'^{\,j}\right]$, $i=\overline{1,n}$, $j=\overline{1,m}$ regarding the importance of the selected partial criteria $k_i(x)$ relatively consistent, then the best decision is chosen using model (4) or (7) for their generalized values $\lambda_i=\lambda_i^*$, $i=\overline{1,n}$, relatively consistent, then the best decision is chosen using model (4) or (7) for their generalized values

$$\lambda_i=\lambda_i^*=\bar{\lambda}_i=\frac{1}{m}\sum_{j=1}^{m}\lambda_i'^{\,j},\ i=\overline{1,n}. \tag{8}$$

If the experts' evaluations turn out to be insufficiently consistent, a re-examination is performed. If it is impossible or inexpedient to conduct a repeated examination, special methods of evaluating the importance of partial criteria are used: reduction of variance, penalization of inconsistency, etc.

In the method of variance reduction (method 3) for ordered series of expert evaluations of weighting coefficients λ_i^j, $i=\overline{1,n}$, $j=\overline{1,m}$ the positions of the lower and upper quartiles are determined. The scores that fall into them are not taken into account when determining the average values $\lambda_i=\lambda_i^*=\bar{\lambda}_i$.

In [11] it is hypothesized that the criteria for which the DMP It is proposed to consider that such criteria are more reliable for the construction of the decision-making procedure compared to the criteria for which the collective opinion of the DMP has a higher degree of uncertainty. Therefore, it is proposed to penalize the inconsistency of experts' advantages by reducing the values of the corresponding weight coefficients (method 4).

The algorithm of this method for determining $\lambda_i=\lambda_i^*$, $i=\overline{1,n}$ assumes the implementation of the following steps [11]:

– determination of the arithmetic mean values of expert evaluations for all weight coefficients:

$$\bar{\lambda}_i=\frac{1}{m}\sum_{j=1}^{m}\lambda_i'^{\,j},\ i=\overline{1,n}; \tag{9}$$

– determination of the entropy of values:

$$E_i = \sqrt{\pi/2} \times \frac{1}{m} \sum_{j=1}^{m} \left| \lambda_i'^{j} - \bar{\lambda}_i \right|, \; i = \overline{1,n}; \tag{10}$$

– determination of the hyperentropy of values:

$$H_i = \sqrt{S_i^2 - E_i^2}, \; i = \overline{1,n}, \tag{11}$$

where S_i^2 – dispersion of the i -th weighting coefficient [12]:

$$S_i^2 = \frac{1}{m} \sum_{j=1}^{m} \left(\lambda_i'^{j} - \bar{\lambda}_i \right)^2; \tag{12}$$

– the ratio [11] is used to determine the estimates $\lambda_i = \lambda_i^*$:

$$\begin{cases} \lambda_i^* = \arg\min \max\limits_{ij} \left\{ \left| H_i \lambda_i^* - H_i \lambda_i^j \right| \right\}, \\ \sum\limits_{i=1}^{n} \lambda_i^* = 1, \; \lambda_i^* \geq 0 \;\; \forall i = \overline{1,n}, \; \forall j = \overline{1,m}. \end{cases} \tag{13}$$

The optimization model of the problem (13) is transformed into a linear programming problem using the following relations:

$$\begin{cases} \min \zeta, \\ H_i \lambda_i^* - H_i \lambda_i^j \leq \zeta, \; H_i \lambda_i^* - H_i \lambda_i^j \geq -\zeta, \\ \sum\limits_{i=1}^{n} \lambda_i^* = 1, \; \lambda_i^* \geq 0 \;\; \forall i = \overline{1,n}, \; \forall j = \overline{1,m}. \end{cases} \tag{14}$$

In this case, the best values of the weight coefficients of the partial criteria $\lambda_i = \lambda_i^*, \; i = \overline{1,n}$ are the decisions to the problem (14).

If the accuracy of determining the weighting coefficients is low, it is recommended to use a universal model (method 5) to evaluate the effectiveness of decisions [4]:

$$P(x) = \left\{ \frac{1}{n} \sum_{i=1}^{n} \left[\lambda_i \, k_i(x) \right]^{\beta} \right\}^{1/\beta}, \tag{15}$$

where β – a parameter that depends on the error in determining (scatter) the weighting coefficients, and determines the trade-off scheme for selecting the best decision.

At $\beta=1$ model (15) allows us to choose the decisions that have the maximum additive utility (4), and at $|\beta|\to\infty$ implement a maximin or minimax scheme to choose compromise decisions:

$$x^{o}=\arg\max_{x\in X}\sum_{i=1}^{n}\lambda_i\xi_i(x), \tag{16}$$

$$x^{o}=\arg\max_{x\in X}\min_{1\le i\le n}\{\lambda_i\,\xi_i(x)\}, \tag{17}$$

$$x^{o}=\arg\min_{x\in X}\max_{1\le i\le n}\{\lambda_i\,\xi_i(x)\}, \tag{18}$$

where X – is the set of admissible decisions.

If the weighting coefficients are defined with an error $\delta=\max_{ij}\left|\lambda_i^j-\overline{\lambda}_i\right|$, the corresponding value of the parameter is determined by the relation:

$$\beta=\log n/\log(1+\delta). \tag{19}$$

To establish the effectiveness of methods for determining the weighting coefficients of share criteria in models of multicriteria decision-making, let us perform their experimental study.

Results of experiments

Consider the problem of parametric synthesis of model (4) and choice, using it, of the best decision from the set of admissible $X=\{x_l\}$, $l=\overline{1,8}$, evaluated by three indicators $k_i(x)$, $i=\overline{1,3}$.

To simplify the perception of the conditions of the problem and the results of the decision variants from the set of admissible decisions are presented using the utility functions of partial criteria $\xi_i(x_l)$, $i=\overline{1,3}$ (5) with a value of the parameter $\alpha_i=1$ (table 1).

The normalized results of the range $[0;1]$ of partial criteria λ_i^j, $i=\overline{1,3}$ significance evaluation by the experts E_j, $j=\overline{1,10}$ are shown in table 2.

Let us determine the generalized values of the importance of partial criteria $\lambda_i=\lambda_i^*$, $i=\overline{1,n}$ by averaging expert evaluations (method 1) (8), calculating medians (method 2), reducing dispersion (method 3), and penalizing inconsistency of expert advantages (method 4).

To perform the constraints of the task $\sum_{i=1}^{n}\lambda_i=1$, $\lambda_i\ge 0$, $i=\overline{1,n}$ let us normalize the obtained estimates by the ratio $\lambda_i=\frac{1}{n}\sum_{i=1}^{n}\lambda_i^*$, $i=\overline{1,n}$ (table 3).

Table 1

Characteristics of the decision variants

x_l \ $\xi_i(x_l)$	$\xi_1(x_l)$	$\xi_2(x_l)$	$\xi_3(x_l)$
x_1	0,9486	0,5840	0,5066
x_2	0,0172	0,9545	0,1645
x_3	0,8194	0,9827	0,0135
x_4	0,2875	0,6911	0,9773
x_5	0,3086	0,3289	0,6844
x_6	0,4463	0,0157	0,7646
x_7	0,9873	0,5088	0,5464
x_8	0,6104	0,5962	0,5965

Table 2

Results of the criteria significance evaluation by experts

E_j \ $k_i(x_l)$	$k_1(x_l)$	$k_2(x_l)$	$k_3(x_l)$
E_1	0,1	0,7	0,2
E_2	0,2	0,6	0,2
E_3	0,3	0,6	0,1
E_4	0,3	0,6	0,1
E_5	0,3	0,5	0,2
E_6	0,2	0,7	0,1
E_7	0,1	0,7	0,2
E_8	0,3	0,5	0,2
E_9	0,2	0,7	0,1
E_{10}	0,2	0,6	0,2

Table 3

Normalized values of the criterion importance estimates

Method \ λ_i	λ_1	λ_2	λ_3
Method 1	0,220	0,620	0,160
Method 2	0,200	0,600	0,200
Method 3	0,226	0,613	0,161
Method 4	0,212	0,596	0,192
Method 5	0,220	0,620	0,160

For the normalized values of the weight coefficients λ_i, $i=\overline{1,n}$ (table 3) using the additive model (4) by methods 1–4 and for the value $\beta=-9{,}6940$, which corresponds to the error (dispersion) $\delta=0{,}12$ by method 5 (15) calculate estimates of the generalized utility of decision variants $P(x_l)$ (table 4).

Table 4

Estimates of the overall utility of the variants

$P(x_l)$	Method 1	Method 2	Method 3	Method 4	Method 5
$P(x_1)$	0,6518	0,6414	0,6538	0,6463	0,3234
$P(x_2)$	0,6219	0,6090	0,6154	0,6041	0,5284
$P(x_3)$	0,7917	0,7562	0,7895	0,7619	0,5439
$P(x_4)$	0,6481	0,6676	0,6461	0,6606	0,3826
$P(x_5)$	0,3813	0,3959	0,3817	0,3929	0,1821
$P(x_6)$	0,2302	0,2516	0,2337	0,2508	0,1105
$P(x_7)$	0,6200	0,6120	0,6229	0,6174	0,2824
$P(x_8)$	0,5994	0,5991	0,5995	0,5992	0,3300

According to the obtained values of the total utility of the variants (Table 4) let us determine on the set $X=\{x_l\}$, $l=\overline{1,8}$ (Table 1) ratio of strict advantage:

$$R_S(X)=\left\{<x_j, x_l>:\ x_j,\ x_l \in X,\ x_j > x_l\right\}. \tag{20}$$

Based on the relations of strict advantage (20) for the set of variants (table 1) the corresponding orders are constructed (table 5).

Table 5

Ordering decisions by utility

Methods	Orders
Method 1	$x_3 \succ x_1 \succ x_4 \succ x_2 \succ x_7 \succ x_8 \succ x_5 \succ x_6$
Method 2	$x_3 \succ x_4 \succ x_1 \succ x_7 \succ x_2 \succ x_8 \succ x_5 \succ x_6$
Method 3	$x_3 \succ x_1 \succ x_4 \succ x_7 \succ x_2 \succ x_8 \succ x_5 \succ x_6$
Method 4	$x_3 \succ x_4 \succ x_1 \succ x_7 \succ x_2 \succ x_8 \succ x_5 \succ x_6$
Method 5	$x_3 \succ x_2 \succ x_4 \succ x_8 \succ x_1 \succ x_7 \succ x_5 \succ x_6$

To clarify the degree of consistency of the order relations of the alternatives, we use the Spearman coefficient (Table 6).

The obtained values of Spearman coefficients for methods 1–4, by means of which the weight coefficients of partial criteria were determined, are close to the one, which indicates small discrepancies in the indicated orders. This is a consequence of the relatively insignificant divergence of the experts' assessments (Table 2).

Table 6

Spearman coefficient

Methods	Method 1	Method 2	Method 3
Method 2	0,952380952		
Method 3	0,976190476	0,976190476	
Method 4	0,952380952	1	0,976190476

Some difference between the evaluations of the total utility of variants and the corresponding order for method 5 (15) and those obtained by methods 1–4 can be explained by its focus on the maximizing scheme of decision-making (17). It presupposes a possible change in the weighting coefficients in the range of $\lambda_i \pm \delta$, $i = \overline{1,n}$ and takes into account the minimum value of the utility function of partial criteria for each of the variants.

Conclusions

The analysis of the current state of the problem of support for multi-criteria design and management decisions found that in many cases, expert assessments regarding the importance of individual indicators can vary significantly, and the individual criteria characterizing the decision variants can be set not by their point values, but in the form of fuzzy sets. The following are the most important criteria of a decision, which can be defined not as their point values, but as fuzzy sets of random values distributed according to some law, or intervals, in which the advantages are not defined.

On this basis, to expand the prospects of intellectualization of design and management procedures for complex objects, the decision of urgent scientific and applied problem of increasing the efficiency of multicriteria decision support technologies by developing a combined method for evaluating variants in conditions of incomplete consistency of expert benefits is proposed. When it is impossible or inexpedient to carry out re-examination to assess the importance of partial criteria, it is proposed to use methods to reduce variance and penalize inconsistency, allowing to increase the accuracy of assessments of the weight coefficients of partial criteria. In cases of low accuracy in determining the weight coefficients of assessment of the effectiveness of decisions it is proposed to use the universal function of total utility, which by changing one of the parameters allows to implement strategies for finding both the most effective and the most sustainable decisions.

Practical use of the proposed method will allow by increasing the accuracy of assessment of weight coefficients of partial criteria to obtain more effective decisions to problems of multi-criteria optimization. The direction of further research may be the development of effective decision support methods for fuzzy or interval characteristics of variants.

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APPLICATION OF THE COGNITIVE APPROACH IN THE FIELD OF PROJECT MANAGEMENT

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The article describes the principles and methods of the cognitive approach to project management. The cognitive analysis and its content are dissected. The essence of cognitive system is considered, and as the cognitive model the example of cognitive map, the methodology of its construction and application is presented and described. The proposed approach allows an expert in a particular subject area to develop the most effective management strategy, based on his experience and, most importantly, on the ordered and verified knowledge of the managed object.

Introduction

Many approaches and methods are used to build modern information systems. In recent years, the cognitive approach, which is understood as the solution of traditional research science problems by methods that take into account cognitive aspects in the processes of perception, thinking, cognition, explanation and understanding, has been actively developed. This approach emphasizes the processes of knowledge representation, its storage, processing, interpretation, and creation of new knowledge.

Nowadays, obtaining reliable information and its operational analysis is the basis for successful management. This is especially relevant if the object of management and its external environment is a complex of complex processes and factors that have a significant influence on each other [1]. Nowadays it is important to use soft management of complex intelligent projects, the essence of which lies in the ways of self-management and self-control. Weak, the so-called resonance phenomena, are extremely effective for self-management, because they meet the internal tendencies of development of complex projects and programs. The main problem is how to push the project to one of its own and favorable paths of development, how to ensure self-management and self-sustaining development by a small resonant influence. One of the most productive solutions to the problems that arise in project and organizational management is the application of cognitive management. The basis of cognitive management is cognitive analysis, cognitive models, cognitive modeling, and cognitive system.

Cognitive analysis

Initially, cognitive analysis was formed within the framework of social psychology, namely cognitivism, which studies the processes of perception and cognition. The application of social psychology's developments to management theory led to the formation of a special field of knowledge, cognitology, which focuses on the study of management and decision-making problems. At present, the methodology of cognitive modeling is being developed in the direction of improving the apparatus of analysis and modeling of situations. Theoretical achievements of cognitive analysis became the basis for creating computer systems aimed at solving applied tasks in the sphere of management.

Examples of cognitive analysis are PEST and SWOT analyses. They are used in strategic management [1]. For example, PEST-analysis (Policy, Economy, Society, Society, Technology), with the help of which the state of the resource is most often determined by the listed subsystems; SWOT-analysis (Strengths – pluses, that is, due to which the studied system can exist; Weakness – minuses, weaknesses; Opportunities – system opportunities; Threats – dangers and threats to the system existence). Similar methodologies of strategic analysis are currently used in UN commissions, for example, when selecting indicators for assessing the sustainable development of territories, states, and cities. Using knowledge about the object, groups of experts analyze the situation in the territory, choose oriented indicators and appropriate initiatives to prevent unfavorable development of this or that scenario. The models of the object under study are most often offered to experts in advance. They (models) create a kind of «framework» and are weakly structured – conceptual, that is, cognitive.

Cognitive analysis is defined by I. V. Prangishvili [2] as «sequential cause-effect structuring of information about processes occurring in the areas under study...». Such processes are described by many factors interconnected by cause-effect chains «if..., then...». The cause-effect chain «if..., then...» in algebra of logic was called sequentia and was used in the practice of problem formalization. The most frequent problems are those of qualitative nature, i.e. cognitive problems. This is achieved by the above-mentioned chains «if..., then...».

Cognitive analysis is sometimes called «cognitive structuring» by researchers. Cognitive analysis is considered as one of the most powerful tools for studying unstable and weakly structured environment. It contributes to a better understanding of the existing problems in the environment, identifying contradictions and qualitative analysis of the processes taking place. The essence of cognitive (gnostic) modeling of the cognitive analysis key point is to reflect the most complex problems and trends of system development in a simplified form in the model, to investigate possible scenarios of crisis situations, to find ways and conditions of their solution in a model situation. Cognitive analysis consists of several stages, each of which carries out a certain task. The sequential solution of these tasks leads to the achievement of the main goal of cognitive analysis.

Cognitive modeling and the cognitive system

Cognitive modeling is designed to structure, analyze and make management decisions in complex and uncertain situations (geopolitical, domestic political, military, etc.), in the absence of quantitative or statistical information about what is happening in such situations. Cognitive modeling contributes to a better understanding of the problem situation, identification of contradictions and qualitative analysis of the system. The purpose of modeling is to form and refine a hypothesis about the functioning of the object under study, considered as a complex system consisting of separate, but still interconnected elements and subsystems.

To understand and analyze the behavior of a complex system, a structural diagram of the cause-effect relationships of the system elements is constructed. The analysis of these relationships is necessary to implement different process controls in the project.

Cognitive modeling allows in an express mode, in the shortest possible time at a qualitative level:

– to assess the situation and analyze the mutual influence of the acting factors determining the possible scenarios of situation development;

– to reveal the tendencies of the situation development and the real intentions of their participants;

– to develop a strategy for the use of trends in the political situation in the national interests of Ukraine;

– to determine possible mechanisms of interaction between participants of the situation to achieve its purposeful development for the benefit of Ukraine;

– to elaborate and ground the directions of situation management in favor of Ukraine;

– to determine possible options for the development of the situation, taking into account the consequences of major decisions, and to compare them.

The use of cognitive modeling technology allows to be proactive and not to bring potentially dangerous situations to threatening and conflict situations, and in the case of occurrence – to make rational decisions in favor of the subjects of Ukraine.

For tasks related to organizational systems, the problem of uncertainty in describing and modeling the functions of the participants is not methodological, but intrinsic to the very subject of research. Different formulations of the problem of situation management are possible, depending on the completeness of the information available to the participants about the situation and other participants, in particular to find resonance and synergistic effects, when the improvement of the situation when several participants affect it simultaneously is greater than the «union» of the positive effects from each of the participants separately.

Cognitive system is often associated with decision support systems (DSS) or the system of management support (ESS – Executive Support System) [3]. A cognitive system is a structured, logically described or formalized model of a «soft» (weakly structured) system proposed for cognitive analysis.

The construction of a cognitive system includes an analysis of the modes of its operation, an analysis of the environment in which it functions. External and internal characteristics of a cognitive system are distinguished. External characteristics characterize the characteristics of the environment. They are denoted by their vector $X = (x_1, x_2, \ldots, x_n)$. Internal characteristics characterize the characteristics of individual parts of the system, they are denoted by a vector $Z = (z_1, z_2, \ldots, z_r)$. The combination of external and internal parameters forms the input parameters. Values characterizing properties of a cognitive system are called input parameters. They are denoted by a vector $Y = (y_1, y_2, \ldots, y_t)$. Combinations expressing the dependence between input and output parameters are considered a mathematical description of a cognitive system:

$$Y = F(X, Z) \tag{1}$$

Expression (1) is a fuzzy relation between two sets of parameters $A = (X, Z)$ and Y.

The modified hierarchy method is often considered to be the main method for constructing a cognitive system. Each level of the hierarchy has its own models. Here is the algorithm of the complex hierarchical approach to building a cognitive system:

1. The number of hierarchy levels in the cognitive system is determined.

2. The main criteria of each level are defined.

3. Initial states of components of the cognitive system and input values of parameters determining initialization of events are established, initial value of modeling time $t = t_0$ is set.

4. Structural, heuristic, simulation, and evolutionary models are constructed.

5. The fuzzy condition scale is set and the simulation path is selected.

6. The logic of feasibility of all events at all levels of the hierarchy in the cognitive system is checked.

7. A list of events L_C for which the initialization conditions are met is constructed.

8. If the list L_C is empty, proceed to item 9. Otherwise, control is given to carry out the procedure of servicing the first event from L_C. The time of this event in the future is modified and removed from the list. Transition to item 6.

9. In the list of scheduled events, the event with the minimum initialization time is found and the time which belongs to this time is corrected.

10. The complex criterion of the whole cognitive system is determined.

11. The condition for completing the complex simulation is checked. If it is not satisfied, we proceed to step 6.

Cognitive model

The notion of a cognitive model is interesting [4]. One of the most common cognitive models is the cognitive map.

It is used in cognitive modeling of complex situations. A cognitive map (cognition map) is a type of mathematical model represented by a graph and allows describing the subjective perception of a person or group of people of any complex object, problem, or system functioning [5, 9]. It is designed to reveal the structure of causal relationships between elements of a system, complex object, constituent problems, etc., and to assess the consequences occurring under the influence of influencing these elements or changing the nature of relationships. Let's consider conditional model of sales at the enterprise (fig. 1).

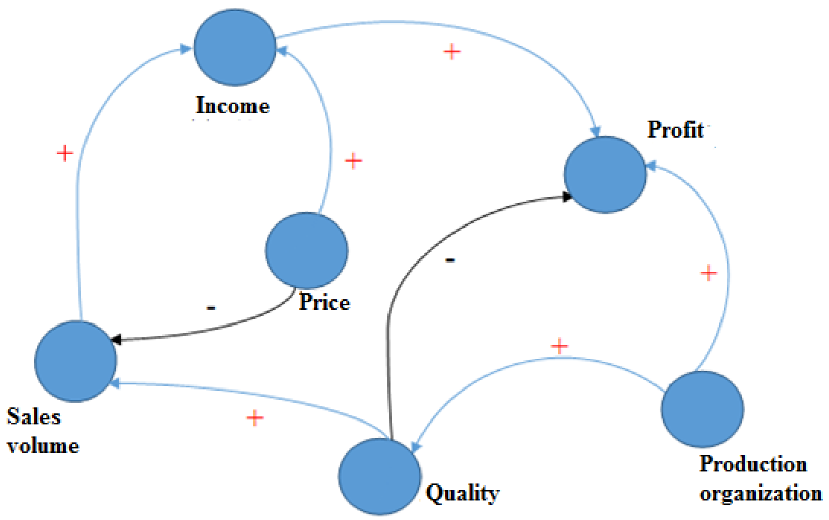

Fig. 1. Cognitive map of sales in a hypothetical enterprise

Here the nodes of the graph are the factors of the situation, and the arcs are the cause-effect relations between them. The plus sign on the arcs between the nodes-factors means that an increase in the value of the factor-cause leads to an increase in the factor-effect, and the minus sign means that an increase in the value of the factor-cause reduces the value of the factor-cause. The cognitive map reflects the functional structure of the situation being analyzed, as a change in the value of a situation factor results in a «front» of change in the values of the factors associated with it. This front of change is called an impulse process in the cognitive map and allows one to obtain predictions of the development of situations.

Let's consider the price-sales volume-income triangle. If you increase the price with a constant volume of sales (in units), the income goes up, it's arithmetic. It's the same when sales volume increases at the same price. But when the price goes up, the sales volume goes down, that's economics. What will be the total effect on income when the price changes? We have to weigh that effect somehow, that is, just the sign of the effect is not enough. To do this, let's first understand what the factors are measured in. Price, income, and profit are in hryvnias, and sales volume is in pieces.And what about the organization of production? You can say about it «it is at the top,» or «it leaves a lot to be desired». The same can be said about various factors of the outside world – «rush demand» or «goods are stale. Here already there are no natural quantitative measures, but it is possible to construct a qualitative scale. This is called «linguistic significance,» and a factor is then said to be a linguistic variable. All factors and, consequently, their changes have quantitative expression, this quantitative expression can be objectively measurable or have a linguistic value that has its own numerical interpretation. The interplay of factors reflected by cognitive maps is essentially a «weighted graph model of the system under study,» and this map is usually completed by a «cognitive analyst».

Consequently, the cognitive model includes a cognitive map (an oriented graph) and the weight of the graph arcs (an assessment of the mutual influence or influence of factors). In determining the weights of the arcs, the oriented graph is transformed into a functional graph.

Within the cognitive approach the terms «cognitive map» and «oriented graph» are often used as equivalent; although, frankly, the concept of oriented graph is broader, and the term «cognitive map» indicates only one of the applications of oriented graph. A cognitive map consists of factors (system elements) and connections between them [5, 10].

In order to understand and analyze the behavior of a complex system, a structural scheme of causal relationships between elements of the system (situation factors) is constructed. Two elements of the system A and B are depicted in the diagram as separate points (vertices) connected by an oriented arc, if the element A is connected to the element of causality: A → B, where: A is the cause, B is the effect.

Factors can influence each other, and such influence, as already mentioned, can be positive, when an increase (decrease) of one factor leads to an increase (decrease) of another factor, and negative, when an increase (decrease) of one factor leads to a decrease (increase) of another factor. And the influence can also have a variable sign depending on possible additional conditions.

The cognitive map displays only the fact that factors influence each other. It reflects neither the detailed nature of these actions, nor the dynamics of the configuration of actions depending on the configuration of the situation, nor the temporal configuration of the causes themselves. Consideration of all these circumstances requires a transition to the next level of information structurization, that is, the cognitive model of the information situation.

At this level, each relationship between the factors of the cognitive map is revealed by the corresponding dependencies, each of which can contain both quantitative (measurable) variables and qualitative (not measurable) variables.

As knowledge about the processes occurring in the situation under study accumulates, it becomes possible to reveal the nature of the connections between the factors in more detail.

There are the following difficulties in constructing a cognitive model: it is difficult to identify the causes; to isolate the essential and secondary factors; to rank the factors; to identify the degree of mutual influence of the factors.

The latter problem is most often solved by applying correlative analysis [6]. Selection of essential and secondary factors can be solved on the basis of the theory of advantages. Identification of factors is carried out on the basis of latent analysis.

Identification of essential factors is possible on the basis of impact analysis [7]. The use of cognitive models qualitatively increases the validity of making managerial decisions in a complex and rapidly changing environment, deprives the expert of «intuitive wandering», and saves time on comprehension and interpretation of events occurring in the system.

Conclusions

The essence of cognitive project management is to help the expert develop the most effective management strategy based on his experience and, most importantly, on the ordered and verified knowledge about the management object [8]. The field of application of cognitive management is constantly expanding. First of all, it is decision-making in the development of states, territories, communities; modeling information wars and conflicts In the end, it is the task of information stability of systems, states, communities; families, as an average element of these groupings, and modeling human behavior as a complex organized biosystem. In our opinion, a promising direction is the development of entropic approach for the evaluation and structuring of information used in cognitive management.

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METHODOLOGY OF ARCHITECTURE-ORIENTED SYNTHESIS IN COMPONENT DESIGN OF AEROSPACE COMPLEXES

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The monograph is devoted to the problem of complex aerospace technique (AST) design using modern design tool based on component representation of multilevel AST structure. The relevance of the research topic is related to the increasing complexity of designed AST products and requirements to reduce development time and minimize design risks.

The aim of the study is to create a new methodology for architecture-oriented synthesis based on a component-based representation of a complex AST structure.

In realizing the goal of the research, the tasks of AST component architecture decomposition; forming a set of components from past experience as well as innovative components; forming a database and knowledge of past experience based on precedents; creating a technology for system design of AST multilevel structure; minimizing design risks and ensuring project feasibility for creating innovative AST products were considered. The methodological basis of the conducted research is a systematic representation of the component multilevel structure of AST with active use of the experience of past developments. The competitiveness of new AST products is achieved by an optimal combination of components from past developments and new innovative components. By using the system technology of top-down synthesis, a multi-level component structure of AST is formed. The new AST product uses a multi-level precedent base of proven components from past AST developments to find the right components. New AST components lead to increased time and risk in the design and affect the feasibility of the project, which is investigated at all stages of the AST development lifecycle. ***Scientific novelty and originality of the study*** *are associated with the formation of a new system methodology based on the component design of complex high-tech products AST and the active use of positive experience of past developments.* ***The mathematical methods used are:*** *system analysis, component design, precedent approach, project management theory, cluster analysis, methods of qualitative evaluations, optimization methods, simulation modeling methods. For managers and specialists of research organizations and industrial enterprises, teachers, students, masters and graduate students of higher educational institutions.*

Introduction

Ukraine has one of the world's largest scientific, technological and production potential for the creation of aerospace technique (AST), research and use of air and space. This potential is the national asset of the country. The basis of the aviation and space potential of Ukraine consists of:

– manufacturing and technological base;

– multidisciplinary experimental base;

– the ground-based facilities of the command and control infrastructure for spacecraft;

– teams of special design organisations, research and academic institutions;

– scientific laboratory and research base;

– educational base of higher school for training of specialists in aerospace professions.

Implementation of the main provisions of the National Space Program provides for the formation of a domestic market of space services, access to the international aerospace market with its own products and services (including space rocket systems and vehicles, information, elements of space systems), creation of ground space infrastructure, deployment of a multifunctional national constellation of space vehicles.

The modern level of created space technology products requires the search for effective methods of analysis and management of projects and programs for their creation [1, 2]. Programs and projects of aerospace industry are characterized by:

– innovativeness of the project content;

– hierarchical organizational structure of the executors;

– distributed structure of enterprises and research centers;

– complicated component composition, multilevel detailed elaboration of systems;

– a high degree of parallel overlapping in the creation of individual components and subsystems;

– enormous flows of design and control information;

– complicated relations between main executors and project co-executors;

– long terms of aerospace complexes development;

– complexity of financing due to large volumes of resources required to create new items;

– high risk level at creation of aerospace systems due to innovativeness s of projects and limited resources;

– the presence of uncertainty and a large number of internal and external random factors affecting the project.

In the works of foreign experts on the problems of complex project management [3], in conditions of uncertainty and economic instability, little attention is paid to the problem associated with the limited resources allocated for the implementation of projects. It is believed that the preliminary project analysis has determined the necessary amount of resources and in the course of project implementation, the resources arrive in the required amount and within the planned time frame. Due to the unstable political and economic situation in the world, the application of existing approaches and methods is very limited.

The works of well-known scientists in the field of theory and methods of complex projects management such as S. D. Bushuyev, I. I. Mazur, F. Clifford, V. D. Shapiro, V. I. Voropayev, V. N. Burkov and others consider solution of separate problems and aspects of projects management: network design methods, planning methods, risk management, resource management, personnel management. The use of these methods is limited to business processes and does not take into account the specifics of science-intensive scientific and technological projects and programs, especially in the field of creating new aviation and space systems, which are financed to a large extent from the state budget.

The analysis has shown that the solution of project management problems associated with the creation of knowledge-intensive equipment, taking into account the multi-component product architecture, limited resources, is not systematically researched, poorly structured, poorly formalized and mainly carried out intuitively, at the level of existing experience. Therefore, the use of modern approaches, methods, mathematical models and information technologies will allow avoiding gross errors at the initial stages of creating aviation and space systems [4, 5], to make correct decisions with minimal risk on project management in conditions of limited resources.

Since the state programs in the field of aviation and space have a large dimensionality, multi-level representation, it is impossible to conduct a reliable analysis of their content without modern information technology [6, 7, 8]. Therefore, the created methods and models of project management, should be developed in the conditions of their further implementation in the form of applied information technologies. Thus, the analysis showed that the existing approaches and methods do not allow to form a sufficiently adequate models for the study of complex projects and programs in the field of creation of AST products, which would fully take into account the system aspects of projects, complex component architecture of products, design objectives and customer requirements, limitations of economic, technical and organizational nature, primarily related to the limited resources allocated to the project. One of the existing disadvantages in solving the problems of management of state programs and complex scientific and technical projects is the lack of a unified methodological framework for project management. The above circumstances determine the relevance of creating a methodology and development of new system methods of architecture-oriented synthesis in the life cycle of aerospace technique design.

Creating Aerospace Architecture Using the Positive Experience of Previous Developments

Using a systematic approach to the design of complex techniques

Depending on the goals of analysis and the level of abstraction, different representations of a complex technical system are known. The most general of them is the set-theoretic description [9, 10]. In our case, a complex technical system is understood as a set M of homogeneous or heterogeneous elements (components), on which a set of relations (connections) R are realized, ordering the elements into a component architecture, which has a set of properties P (technical specifications of the technical task), allowing to achieve a given goal in the functioning of the system. The ordering of the set of elements and relations between them form the architecture of a complex technical system of the form:

$$C = (M \times R). \quad (1)$$

Concretization of the set-theoretic description of a technical system is connected with the definition of sets M, R, P. In this case, the sets are finite and lend themselves to information description only if the level of detail of the set of elements (components) is defined. Any description of a complex technical system at the initial stage of synthesis is an abstract model. The definition of such a model is closely related to the introduction of an abstract language reflecting the problem domain. An abstract language has a specific alphabet (a finite set of technical concepts), in which the grammar, i.e. the rules of ordering and manipulation of the alphabet signs are specified. Depending on the language, models of description of technical systems can be verbal (natural language), graphic, mathematical, etc.

The problem of synthesizing a technical system includes the following tasks:

Definition of the goal and the task of the technical system. The goal is some required state of the technical system, the achievement of which is associated with the performance of purposeful actions to create it. The state of the system is described by the value of the properties measured in a certain metric of technical characteristics.

Analysis of the goal and allocation of the properties that the technical system should have as a result of its synthesis. At the initial stage, the goal is most often presented in the form of a generalized verbal statement of the customer of the technical system. Further analysis of the created technical system involves the allocation and measurement of functional properties required to achieve the synthesis goal. As a rule, it is necessary to define some set of properties of technical system, each of which characterizes a local functional quality, and together they fully enough characterize the system as a whole, i.e. represent a set of technical characteristics of the system. Thus, a technical system is characterized by a set of properties, which should be obtained in the process of synthesis:

$$P = \{p_1, p_2, ..., p_n\}. \quad (2)$$

Properties of a technical system in the form of its characteristics have different functional meaning, dimensionality, intervals of possible values and are measured in different scales. On the one hand, the set of properties must be limited, i.e. take into account only the most important defining properties of the technical system, and on the other hand, it must completely enough characterize the system and its capabilities in the process of functioning.

Determination of a possible set of technical system architectures C' that have the required properties (evaluation task). The set C' contains possible variants of constructing a technical system, which are formed by a designer, differing qualitatively, i.e. by sets of elements M and/or relations R; or quantitatively, i.e. by values of parameters (characteristics) of elements and/or relations at the same property. The set C' defines the area in which the synthesis of a technical system with the given properties P is carried out. It should be borne in mind that the mapping of properties P on the sets M and R, and the selection of a subset of the technical system architectures C', on which they are attainable, may have different degrees of uncertainty, which complicates the task of synthesizing a technical system. If the specification of the technical system class, its purpose and the main characteristics (properties) fully and unambiguously enough defines its components (elements) and their relationships (relations), then there is a problem of applied synthesis (design) of the technical system.

Selection of the best option from the possible set of technical systems C' (optimization problem). The ultimate goal of the decision-making problem in the synthesis of a technical system is to choose a rational solution from the admissible set of solutions. The criterion of effectiveness for evaluating solutions should take into account both the positive effect (the degree of achieving the goal in the process of designing a technical system), and the costs and time to achieve it, taking into account the possible risks. In general terms, the goal of the synthesis of the system is characterized by obtaining specific values of the property p_1, and the level of its achievement – the fulfillment of the requirements of the technical specification. Thus, the comparison of the obtained design solutions can be carried out according to the achieved level of particular properties (particular criteria). For relatively simple systems, the choice of an optimal solution is single-criteria with a single solution. In the case of a complex technical system, the synthesis problem is multi-criteria, its unambiguous solution can be obtained only in particular cases, and in the general case it is required to obtain a complex solution that satisfies contradictory criteria.

The method of synthesizing the architecture of a technical system using the experience of previous developments

When creating a technical system, much attention is currently paid to the use of positive experience of past developments. The analysis has shown that the use of positive experience of past developments allows to reduce the risks associated with the creation of the system, to reduce the time and cost of development. The key task at the initial stages of AST product creation is the synthesis of its architecture.

Let us analyze the process of synthesizing the architecture of a complex technical system using a formal representation of the positive experience that is formed as a result of previous similar projects.

One of the ways to use the accumulated experience is to represent design solutions in the form of precedents. The methods of the theory of precedents allow formalizing the description of problem situations and their solutions, which can be used to find successful technical solutions [11 – 13], which can be used in the creation of new AST products. The search for relevant precedents is performed at the product level. Decomposition can then be used to find precedents in the form of solutions for components of different levels of complexity. In turn, the component approach, which has characterized itself well in the design of information systems, does not involve a complex way of formalizing the description of individual components. The formation and search for components was performed by the designer on the basis of his knowledge and experience.

The joint application of the component approach and the theory of precedents allows to form the architecture of a complex technical system using the experience of past developments, which is formalized on the basis of the theory of precedents and can be represented as a multilevel base of precedents [14].

The study has shown that the component approach and the theory of precedents allow us to form components of AST products from past experience in the form of precedents and taking into account their degree of novelty.

To describe precedents you can use a description with features. To each precedent, descriptors of description $(...01001...)$ or sets consisting of tuples $(\{...\},\ \{C_i\},\ \{...\}$ of type $C_i =< n,\ v,\ i,\ r >$, where n – property name; v – its value; i – importance or informational weight of property; r – restriction on interval of acceptable values) are put in correspondence. The restriction defines the interval of values, within the limits of which the property value can determine the value of the measure of similarity between precedents.

The method of creating the architecture of a complex technical system AST using the positive experience of past developments can be represented as an iterative process consisting of several stages. The scheme of the method is shown in fig. 1.

Stage I. The formation of ways to achieve the goal when creating a complex technical system AST is carried out by selecting a preliminary set of existing (obtained in past projects) samples of complex technical products, information about which (technical characteristics (TC), characteristics of the design work to create a technical system) is formed and stored in a precedent base (PB).

For each created sample of complex technical article AST a set of technical requirements (TR) is formed, which are formulated in the technical specification (TS). The products, which are the most «close» by parametric features, will be included in the preliminary set of promising samples of complex technical products, which is used for further research. By a product sample we will understand a unit of a particular product, which is used as a representative of this product in the process of synthesis of a complex technical system.

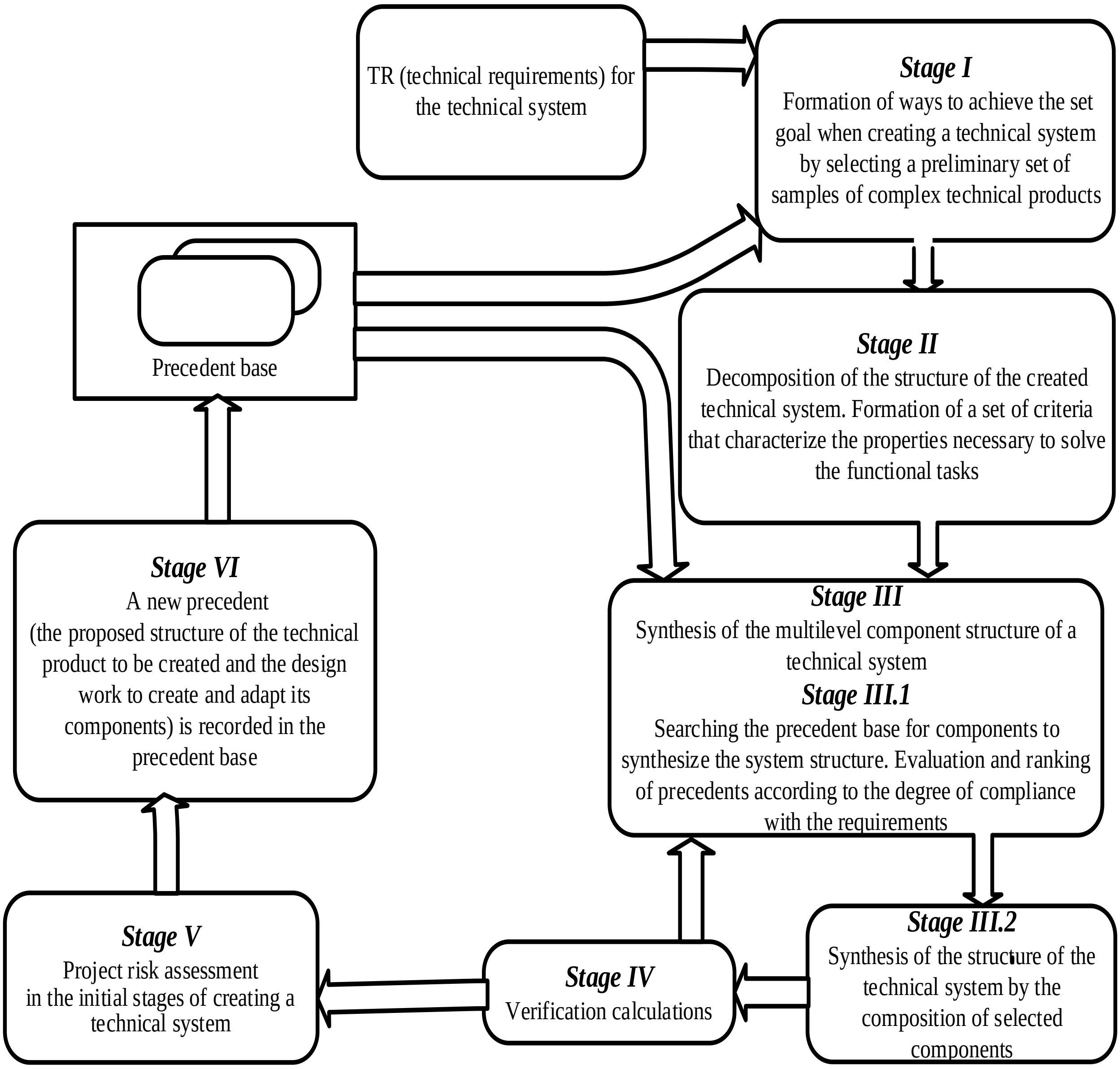

Fig. 1. Scheme of the method of synthesis of a complex technical system using the positive experience of previous developments

Stage II. A complex technical system is broken down into component parts (components), each of which solves a certain set of functional tasks, ensuring the achievement of the goal of creating a complex technical system. Based on the functions performed by each of the components, a set of criteria (technical characteristics), characterizing the ability of the component to perform the assigned tasks in the process of system functioning, is formed.

In the process of decomposition of the architecture of the AST technical system being created, a set of criteria is formed that characterize the properties necessary to solve the functional tasks at each level of decomposition. Thus, functional and criterial decomposition of the system is performed. Since each complex technical product AST being created is unique and it is difficult to find its complete correspondence in past developments, then the components of the systems included in the obtained preliminary set of close samples of technical systems are further considered. The analog will be understood as a technical product or component, the purpose and TS of which are close to the purpose and TS of the new product being created. Decomposition of a technical system into component parts (subsystems, units, assemblies, blocks, etc.) allows us to look for analogs of created components at lower levels of detail of technical system architecture and use them to synthesize a new complex AST technical product.

Stage III. The third stage is the direct synthesis of the multilevel component architecture of the complex technical system AST.

The search in PB for relevant precedents in the form of components taken from past experience is performed. A «top-down» movement through the levels of detail of the system for the synthesis of its architecture is performed. Precedents are evaluated and ranked according to their compliance with the requirements to the components of the system to be created. The selected ready-made components from the past design experience can be further adapted to the TS requirements, based on the features and technical characteristics of the product being created.

Next, the architecture of the AST technical system to be created is formed by composing the selected components from PB at the appropriate levels of system detailing.

Stage IV. Verification of compliance with the requirements taking into account system-wide characteristics (TS characteristics) is performed using methods specific to this subject area, related to the creation of aerospace technical systems.

Stage V. The design risk assessment is carried out at the initial stages of the creation of a technical system. For this purpose, for each component of a complex technical product, a tree of design activities is built. The risk on each group of works and further on creation of all system is estimated.

Stage VI. The resulting synthesis precedent in the form of component architecture of AST product, in the creation of which reuse components, new components and modified (adapted) reuse components can be used, taking into account the formed composition of the design work, is written in PB as a new precedent for further use in subsequent projects to create AST products.

Formation of a preliminary set of analogues of the designed product

In the process of forming and using the precedents database, a large amount of design information is accumulated, describing the solutions of various synthesis problems. Part of the accumulated information may not be applicable to the solution of a particular design problem due to significant differences in the purpose and TC of the created system and the precedents available in PB. In addition, when precedents are used in PB for a long time, some of the accumulated information from past projects becomes obsolete. Therefore, to synthesize the architecture of the created system it is reasonable to form a preliminary set of AST samples, including the products that are the closest by parametric features relatively «fresh» to the created new AST system.

As you know, the effectiveness of the search for precedents that represent AST products with their characteristics depends largely on the knowledge of the subject area and the ultimate goal of the synthesis problem.

Let us briefly analyze the methods that are used to find the measure of similarity (proximity) of the precedents at the initial stage of creating a complex system. The most popular and frequently used is the nearest neighbour method [15], which is often used as a modification (K-nearest neighbours) [16]. This method is quite stable, because it allows to smooth out individual outliers, random noise, always present in the data. There are also many approaches and methods for analyzing and mining data (data mining) in precedent-based inference systems, which focus on the selection of relevant precedents. Such systems use a variety of methods to mine and evaluate the resulting data, among them are decision trees, Bayesian networks, neural networks, etc. All of them offer one or another way to measure the closeness of the precedent and the considered variant of the project solution. For planning and content management processes, it is acceptable to use the precedent approach by applying a heuristic similarity metric.

For complex systems, which include AST products with complex multilevel architecture, the search for the most suitable precedent using the above methods may not give a correct solution. This is due to the increased dimensionality and complexity of the AST synthesis problem. Such problems require the formation of many relevant precedents. Before searching for precedent-components at different levels of the hierarchy of technical products (close analogues), it is advisable to first identify a preliminary set of close samples of complex technical products, which, in turn, ensures the further effective achievement of the project goal when creating a complex technical system. The allocation of a preliminary set can be carried out by parametric features (for example, by performance characteristics) and the target purpose of the AST. A classification method can be used to perform a pre-selection of precedents.

Allocation of a preliminary set of precedents at the product level will allow to carry out the subsequent search of relevant precedents, taking into account the decomposition at the level of individual components (for example, subsystems) in the synthesis of a new AST product. Let us consider the allocation of a preliminary set of precedents using parametric features.

In order to form a preliminary set of precedents we can use cluster analysis. We will use hierarchical agglomerative clustering method to synthesize AST architecture [17, 18]. Agglomerative clustering is a method based on partitioning. The advantages of the method are that agglomerative clustering method allows not to determine the number of clusters in advance. It is well applicable for clustering sets of not very large volume, which is often found in practice. The method often leads to better results than clustering methods based on top-down clustering. A significant advantage of hierarchical clustering methods is the possibility of visual interpretation of the performed synthesis of the architecture of a complex product.

Based on the accumulated information about the values of technical characteristics (TC) of the designed AST products accumulated in past projects, an R_{IJ} matrix is formed, in which the set of rows I represents the designed AST samples (objects), and the set of columns J represents the values of their characteristics. The elements of the R_{IJ} matrix form the input data.

Let's evaluate the importance of each AST product characteristic with the help of importance coefficient W_j. When forming the R_{IJ} matrix, the characteristics are ranked taking into account the importance coefficients, so the calculations take into account only those characteristics whose importance coefficients exceed the given threshold values Ω_j $\left(\Omega_j \le W_j < 1,\ 0 \le \Omega_j < 1\right)$, obtained with the help of expert evaluations. Thus:

$$R_{ij} = W_j \times r_{ij}, \tag{3}$$

where r_{ij} – object i characteristic j value.

At the first step all objects are considered as separate single-element clusters. The distances between all possible pairs of objects are calculated using one or another metric. To obtain a matrix of distances between objects D_{IJ} one can use a special case of Minkowski metrics such as the Euclidean distance [19–21]. In this case, the features are represented quantitatively. The components of the observation vector are homogeneous in their physical meaning and all of them are equally important in terms of solving questions about the assignment of an object to one or another cluster:

$$d\left(i,i'\right)=\sqrt{\sum_{j=1}^{k}\left(i_{norm}^{(j)}-i_{norm}'^{(j)}\right)^{2}}, \tag{4}$$

where $i_{norm}^{(j)}$ – normalized value of the object i characteristic j $\left(j \in J\right)$;

k – the number of characteristics selected based on the importance value Ω_j threshold.

The normalization of the values of the characteristics of the objects is carried out by the formula:

$$i_{norm}^{(j)}=\frac{i^{(j)}-i_{\min}^{(j)}}{i_{\max}^{(j)}-i_{\min}^{(j)}}, \tag{5}$$

where $i^{(j)}$ – object i characteristic j value $\left(j \in J\right)$;

$i_{\min}^{(j)}$ – minimum characteristic j value;

$i_{\max}^{(j)}$ – maximum characteristic j value.

In the process of using the agglomerative hierarchical clustering method based on the estimation of the average relationship [17], the following notations are used:

$X\left(I\right)$ – hierarchical clustering (this is the set of non-empty subsets of the set I, partially ordered by the relation of inclusion of sets);

$T\left(X\left(I\right)\right)$ – the set of terminal clusters of the hierarchy $X\left(I\right)$;

$M\left(X_0\right),M\left(X_1\right),...,M\left(X_{|I|-1}\right)$ – the sequence of nested partitions;

$\nu\left(a\right)$ – cluster a level index (stratification index or cluster diameter);

$\delta_0\left(\{i\},\{i'\}\right),\delta_1\left(\{i\},\{i'\}\right),...,\delta_{h-1}\left(\{i\},\{i'\}\right)$ – distances between clusters;

h – step;

N – nonterminal cluster;

$Si(a)$ – set of clusters directly under the cluster a, the set is a partition of the set a;

$|I|$ – number of elements of the set I;

$A(N)=i$ – node N successor;

$B(N)=i'$ – second node N successor;

$P(N)=2$ – number of nodes N elements;

s_h and s'_h – two clusters of $M(X_{h-1})$, on which the minimum value of distances δ_{h-1} at $M(X_{h-1})$ is realized.

It is necessary to build a sequence of partial hierarchies $X_0, X_1, ..., X_{|I|-1}$.

<u>Start.</u> The distance matrix $d(i,i')$, calculated from the initial matrix R_{IJ}, using the chosen metric, is considered. It is assumed that:

$$X_0 = X_0(I) = T(X(I)) = \{\{i\}; i \in I\},$$

$$M(X_0) = X_0(I) = T(X(I)) = \{\{i\}; i \in I\},$$

$$\nu(\{i\}) = 0,\ (i \in I).$$

It is accepted that the distances between single-element clusters should be equal to the distances between elements:

$$\delta_0(\{i\},\{i'\}) = d(i,i'),\ (i,i' \in I). \tag{6}$$

<u>Step</u> $h=1$. The minimum value δ is searched at X_0. Let this minimum value is achieved on a pair of single-element clusters $\{i\}$, $\{i'\}$. Then the first node is formed with a consecutive number $|I|+1$, so that $N=|I|+1$ and $h=1$ we assume:

$$a_1 = \{i,i'\},\ Si(a_1) = \{i,i'\},\ |a_1| = 2,$$

$$M(X_1(I)) = M(X_0(I)) \cup \{a_1\} \setminus \{i\} \setminus \{i'\},$$

$$X_1 = X_1(I) = X_0 \cup a_1, \tag{7}$$

$$\nu(a_1) = \min\{\delta_0(i,i') : i \neq i',\ i,i' \in M(X_0)\} = \nu(N).$$

Finally, the distances between all clusters of the new partition, denoted by $M(X_1)$ is calculated. Since it is obtained from $M(X_0)$ by combining two clusters, it is necessary to use the distance characteristic between two subsets of elements to recalculate the distances. Then we can calculate the distance between the new combined cluster and other clusters:

$$\delta_1(a_1,t),\ (t \in M(X_1)).$$

We will consider as a characteristic (criterion) of the distance between two subsets of elements the average distance between the subsets (clusters). The distance between a new cluster and other clusters $\delta(a,\, b)$ (where a and b are two subsets (clusters) I) is calculated by the average relation method:

$$\delta(a,\, b) = \sum\{d(i,i');\ i \in a,\ i' \in b\} / |a||b|. \tag{8}$$

The average relationship method uses information about all distances between pairs of clusters. The distance between two clusters is defined as the average of the original distances between elements belonging to those two clusters. The recurrence formula has the following form:

$$\delta_h(t,\, s_h \cup s'_h) = \left(|s_h|\delta_{h-1}(t,\, s_h) + |s'_h|\delta_{h-1}(t,\, s'_h)\right) / \left(|s_h| + |s'_h|\right), \qquad (9),$$

at $t \neq s_h \neq s'_h;\ t,\ s_h,\ s'_h \in M(X_{h-1})$,

$$\delta_h(t,\, t') = \delta_{h-1}(t,\, t'), \tag{10}$$

at $t \neq t' \neq s_h \neq s'_h;\ t,\ t',\ s_h,\ s'_h \in M(X_{h-1})$.

<u>Step</u> $h = Z$. The sequence of nested hierarchies X_{h-1}, and the vertex $M(X_{h-1})$ are known. Recurrence formulas, to be efficient, must be based only on information related to $M(X_{h-1})$. We obtain:

$$N = |I| + h,$$
$$a_h = s_h \cup s'_h,\ Si(a_h) = \{s_h,\ s'_h\},$$
$$X_h(I) = X_{h-1}(I) \cup a_h,$$
$$M(X_h(I)) = M(X_{h-1}(I)) \cup \{a_h\} \setminus \{s_h\} \setminus \{s'_h\}, \tag{11}$$
$$\nu(a_h) = \min\{\delta_{h-1}(s,\, s');\ s \neq s',\ s,\ s' \in M(X_{h-1})\},$$
$$|a_h| = |s_h| + |s'_h|.$$

So that $\nu(N) = \nu(a_h)$, $A(N)$ and $B(N)$ – numbers of clusters s_h and s'_h in the hierarchy V_i, accordingly $P(N) = P(A(N)) + P(B(N))$.

When recalculating distances for $\delta_h(t, a_h)$, $t \in M(X_h)$ the following values are used:

$$\delta_{h-1}(t,\, s_h),\ \delta_{h-1}(t,\, s'_h),\ \delta_{h-1}(s_h,\, s'_h),\ \nu(s_h),\ \nu(s'_h),\ |s_h|,\ |s'_h|, \nu(t),\ |t|.$$

The last step $h = |I| - 1$. It remains to combine only two clusters to get the whole set I. In this case:

$$N = 2|I| - 1,$$
$$a_h = I = s_h \cup s'_h,\ |a_h| = |s_h| + |s'_h| = |I|,$$
$$X_h = X_{|I|-1} = X(I), \tag{12}$$
$$M(X_h) = \{I\},$$
$$\nu(a_h) = \nu(I) = \delta_{h-1}(s_h,\ s'_h).$$

As a result, at the end of the clustering process, all objects become members of one single cluster.

By performing the clustering process according to the maximum permissible distance measure between clusters Υ, chosen by the experts, we obtain a preliminary set of precedents on the level of individual samples of technical products, which is formed according to parametric features. The objects belonging to clusters, the distances between which exceed the maximum permissible distance measure Υ set by the experts, are excluded from further consideration.

Decomposition of the system component architecture

Functional and criterial decomposition of an AST product, and subsequently a set of design work on the development of individual components of the product is an important process in the synthesis of the architecture of a complex system [22].

Decomposition allows to divide a complex system into smaller parts with the purpose of subsequent connection for a more detailed representation of the composition of the complex system.

Decomposition of complex problems into simple elements (components) is one of the main methods in system design using top-down technology. Decomposition is used for subsequent synthesis of a complex AST technical system.

The allocation of a preliminary set of samples (close analogues) of complex technical products makes it possible to narrow the area of search for precedents at the component level when synthesizing the architecture of a new AST product. After the preliminary set of precedents is obtained, the process of functional and criteria decomposition of created technical products into components and partial criteria, characterizing the properties necessary for solving functional tasks, is performed. This makes it possible to search for relevant precedents at lower levels and to find suitable precedents for the components selected as a result of the decomposition process.

Using functional decomposition, any product can be broken down into its individual components. Depending on the level of decomposition, AST architecture can be represented as a set of basic components inherent in that level.

The decomposition tree U of the product architecture is a multilevel component hierarchical AST product architecture. After completion the decomposition process, taking into account the selected preliminary set for the search of precedents by parametric features, we obtain a multilevel hierarchical product architecture, which is represented in the form of component composition of a technical product. In turn, as a result of functional and criterion decomposition of developed AST products, we obtain the architecture of design works, which allows us to distinguish the subtrees of design works for the development (adaptation) of those or other components that are included in the architecture of a new AST product.

To decompose the architecture of a technical system, a set-theoretic description is used:

$$C_j^u = \left\{ \left\{ C_1^{u+1} \right\}, \dots, \left\{ C_i^{u+1} \right\}, \dots, \left\{ C_{n_u}^{u+1} \right\} \right\}, \tag{13}$$

where C_j^u – j-th component of the u-th level decomposition of the product architecture;

$\left\{ C_i^{u+1} \right\}$ – a subset of embedded components in a complex component C_j^u of the lower level $u+1$;

u – number of the decomposition level of the architecture of the complex AST product that is created;

n_u – the number of components of the u-th level of AST product decomposition.

Product components from a selected preliminary set of technical product samples can be described in the form of a tuple of their technical specifications. In the same way the TS requirements for the components of a new product can be presented:

$$C_j^u = \left\langle h_1,\ h_2, \dots, h_{s_{ju}} \right\rangle, \tag{14}$$

where C_j^u – a tuple of characteristics (properties) taken from TS, which describes the j-th component of the u-th level of AST product decomposition;

$h_1,\ h_2,...,h_{s_{ju}}$ – values of technical specifications (requirements);

s_{iu} – the number of technical characteristics (requirements) for the component j of the u-th level of architecture decomposition of the designed AST product.

Architecture-Oriented Synthesis of the Multilevel Component Structure of a Technical System

Creating a precedent base from previous development components

The architecture of the AST technical system implies a relatively stable organization of its individual components with their interrelationships, which are formed taking into account the goals and functions performed during the functioning and operation of the system.

Modern AST product architecture contains a large number of components taken or adapted from previous developments.

The proposed approach based on the active use of positive experience of the past will minimize the risk associated with the creation of new components and will provide significantly lower development costs and reduce the time of AST product design, as well as increase the feasibility of the technical system creation project. The emergence of new functional tasks, and hence design work, is associated with the need to create new innovative components. Therefore, when creating AST products, it is necessary to find a compromise in the formation of AST product architecture, which will include both reusable components and new components.

Many years of experience with AST products allows developers to identify the main component types inherent in each detail level of AST products.

To synthesize the multilevel component architecture of a technical system, it is reasonable to use the precedent approach. The joint application of the component approach and precedent representation of components allows to formalize and automate the initial stages of AST product development, taking into account the positive experience of past developments, and is used to form a multilevel architecture of new AST products. The proven components of a decomposed product can be represented as precedents at different hierarchical levels of the created multilevel precedent base, which corresponds to the hierarchical architecture of an AST product.

As mentioned earlier, the AST product architecture consists of three types of components. These include reusable components (RUC) that do not need to be adapted, RUC that need to be modified and adapted (MRUC), and new innovative components (IC). In addition, complex combined components (CC) can be distinguished in a multilevel architecture, consisting of RUC and IC.

Each precedent can be represented in the form of an information module that describes the technical characteristics (TC) of a component r and the design work associated with its creation. Let us represent the technical characteristics of a component r in the form of a tuple Q_r, each element of which corresponds to a specific technical characteristic.

The requirements for the creation of an individual AST product component contained in TS can also be formalized as a tuple of specifications Q_s describing a problematic design situation, the resolution of which can be carried out with the help of the created precedents base (PB). By a directed search and comparison of requirements Q_s and each Q_r of the set of PB components, it is possible to find precedents (RUC) at the given i-th level of AST product architecture representation. If the found «close» Q_r components at the considered level do not satisfy the designer, then the designer moves to the next (lower) decomposition level ($i+1$) and continues to search for «close» precedents of that PB level.

Thus, AST product architecture synthesis is a systematic search procedure consistent with top-down ideology, and used for precedents in the multilevel PB of components taken from existing AST product designs.

Note that at zero, the uppermost level of decomposition in the multilevel PB, each element represents a complex technical product that has been previously developed. At the first level of PB decomposition, precedents are represented by the main functional subsystems, which are described by their technical characteristics (TC). PB also contains descriptions of the design work performed to create these subsystems or complexes. Subsequent levels of PB contain RUCs with varying degrees of detail of the multi-level architecture of AST products.

Let for each component of the AST product to be developed, taking into account the decomposition level of the architecture, there exists a set of precedents in PB in the form of components of past developments. Let us assume that this set has been previously formed by the experts and developers of AST products.

It is necessary to find in PB the subset M_{ie}^{*}, which is «closest» to the technical characteristics of the AST component s_{ie} required by TS (a problematic design situation arises). To perform search operations in PB, we conduct a preliminary ordering of precedents, which should be performed at each level of decomposition of AST product architecture i for the e-th component name.

It is convenient to use lexicographic ordering for preliminary ranking of precedents.

As we know, lexicographic ordering corresponds to sequential optimization and it can be used to solve the problem of rational choice of the best option from a possible set of options. The idea of this method is to solve a system optimization problem by ordering the elements or characteristics of the system.

To do this, all partial criteria are ranked in descending order of importance, that is, the following linear order is established:

$$k_1 \succ k_2 \succ \ldots \succ k_n, \tag{15}$$

where $\succ$ – sign of preference relationship.

In the resulting sequence it is possible to solve single-criteria optimization problems for each partial criterion. The method of sequential optimization corresponds to the rule of word ordering in alphabetical order when creating dictionaries, therefore, it is called the method of lexicographic ordering [23, 24].

Each component (precedent) of a technical system can be represented in PB as a «word» (tuple) of technical characteristics [25, 26]. The specifications in the «word» are ranked by importance.

The value of the most significant technical characteristic of the component is on the first place of the «word», and the value of the least significant one is on the last place of the «word». To facilitate the search, let us translate the values of all technical characteristics of AST product components into qualitative values of linguistic variables l_{ieb}, where i is the decomposition level of AST product architecture, e is the name of the component, b is the technical characteristic.

Let the qualitative value of any linguistic variable l_{ieb} correspond to the letters of the Latin alphabet.

For example:

A – the best value of the characteristic;

B – excellent value;

C – good value;

D – satisfactory value.

Let the designers set ranges of quantitative values for specific TC components, which can be associated with the qualitative values of each linguistic variable.

The search for rational solutions involves translating the quantitative values of TC components into qualitative values and arranging them within «words» based on the importance of the characteristics. The use of lexicographic ordering ensures a directed search and comparison of requirements Q_s with each precedent Q_r taken from PB.

As a result of the lexicographic ordering, the whole set of precedents M_{ie} of a given decomposition level can be represented as an ordered list. In the ordered list of precedents, the precedents that are the closest in TC to the TS component s_{ie} of the designed AST product will be found first.

The number of precedents Q_r from this list, for further consideration and optimization, can be selected at the designer's discretion based on design experience. The selected precedents from the created ordered list are presented as a subset M_{ie}^*.

Any *r*-th component (precedent) in PB is represented as a tuple («word») Q_r with elements in the form of values of technical characteristics (the most significant characteristic is on the first place, and the least significant one is on the last place). For example:

$$Q_r = A_r C_r A_r B_r \ldots.$$

The lexicographic ordering of precedents in PB and requirements for designed components used in the following study has several advantages. These include:

– the TCs in the «word» component are ranked by importance, enabling the search for precedents and therefore required components for different levels of the AST product architecture hierarchy, focusing on the highest-priority characteristics of the component;

– value ranges or specific TC values presented as qualitative values (*A*, *B*, *C*, *D*, ...) correspond to certain values of linguistic variables and allow to objectively consider the customer's wishes;

– regardless of whether the TC are represented by qualitative or quantitative values in PB, all TC for each component of an AST product are represented as a «word» consisting of qualitative values of linguistic variables, each responsible for a particular TC for a given decomposition level of an AST product;

– the search for the «closest» components is performed based on the comparison of the ordered values of the technical characteristics of the precedents and the components required in TS, which provides a convenient and automated search in the multilevel PB.

It should be noted that the lexicographic ordering of the technical characteristic precedents of the designed components is performed at a given level of product decomposition in multilevel PB.

If the designer finds it necessary to look «deeper» into the product and search for suitable precedents at a lower level of AST product architecture, then the lexicographic ordering in PB and component requirements at a lower decomposition level must be performed.

Let us consider an illustrated example.

Let the following fragment (set of «words» M_{ie}) of PB be formed for the AST product i architecture decomposition level for the component name e:

1. ABAD…
2. BACA…
3. BCAD…
4. AABC…
5. ABAC…
6. AACB….

Let the problem situation s associated with the creation of a component of a new AST product has the following ordered «word» of specifications (values of the characteristics of the sought precedent, which coincide with the situation s will be the best in terms of customer requirements):

$$Q_s = AABB....$$

Let us perform a lexicographic search in a fragment of given words PB and generate a list of several «closest» precedents to the required one. The selection can be made at the discretion of the AST product designer.

The selected «closest» precedents to the *s*-th problem situation under consideration are elements of the subset M_{ie}^{*}.

An ordered list of «close» precedents corresponds to the set of M_{ie}^{*} and has the following form:

$$h = 4 : AABC...$$
$$h = 6 : AACB... .$$

where *h* – the number of «word» in the ordered list of precedents (components). From this we see that the first «word» is the highest priority for the choice of the precedent.

Method for the synthesis of a multilevel component architecture of a technical system

Let us form the stages of the proposed method of system synthesis of multilevel AST product architecture using component approach (fig. 2):

1. The zero level of decomposition $(i = 0)$ is the AST product itself. The first problem situation arises related to the development of functional subsystems (individual components at the level of AST product subsystems), so the next level of hierarchy in the system synthesis problem will be the first level.

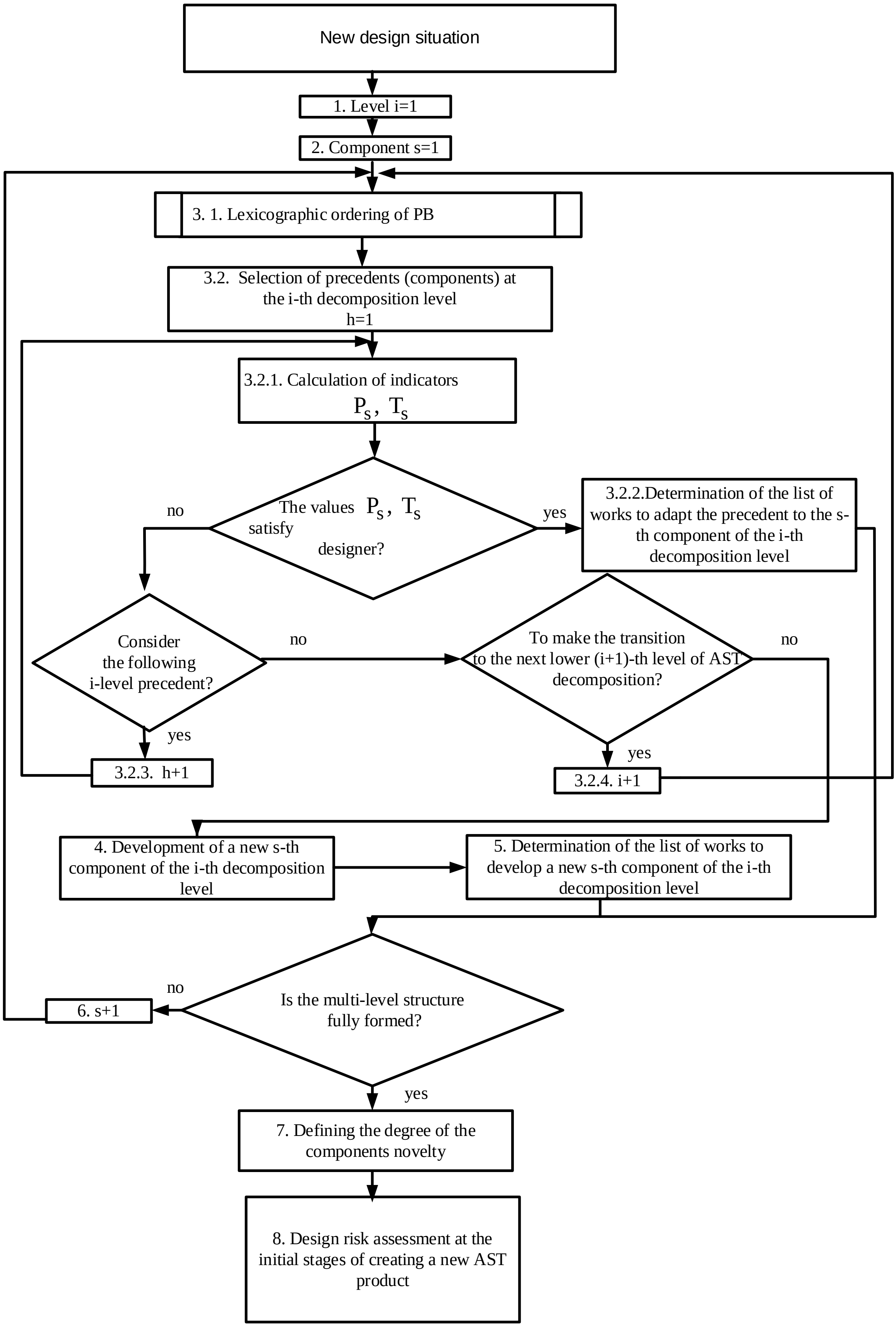

Fig. 2. Schematic diagram of the system synthesis method for the multilevel component architecture of an AST product

Therefore, at the very beginning of the system synthesis of AST product architecture, the search for suitable precedents in multilevel PB is performed at the first level of decomposition: $i=1$.

2. Let us consider the first component in the form of a particular subsystem AST. Let us search for precedents in PB for the first projected component $(s=1)$ of the decomposition level i.

3.1. Let us perform lexicographic ordering of PB (the scheme of lexicographic ordering of PB for preliminary selection of components for further consideration and analysis is presented in fig. 3).

3.2. Let us select the precedents (components) in PB for the projected s-th component at the i-th decomposition level.

3.2.1. Let's estimate the possible costs of adapting (modifying) the selected ready-made solution or, if necessary, the development of a new component P_S. To do this, the time to adapt the selected ready-made solution or the development of a new component T_S is estimated in advance (model to calculate the indicators: costs P_S and value T_S will be given in subsection 2.3).

3.2.2. If the obtained values P_S and T_S satisfy the designer, then the definition of the list of design works on the possible adaptation of the selected precedent to the s-th component of the i-th level of AST product decomposition is carried out.

3.2.3. If the values P_S and T_S do not satisfy the designer, he is suggested to consider the next precedent of $(h+1)$ i-th decomposition level from the list obtained as a result of lexicographic ordering (fig. 3).

3.2.4. If the obtained values P_S and T_S do not satisfy the designer and he does not want to consider other precedents (item 3.2.3) from the list obtained at stage 3, then the AST product is further detailed and moves to the next (lower) $i+1$ level of AST product architecture, and the iterative design algorithm repeats from stage 3 onwards.

4. If the designer does not want to move to the next (lower, $i+1$) level of the AST product architecture to search for precedents in PB, then move to the new component development phase for the i-th level of the AST product architecture.

5. A list of design work to create a new component s for the i-th level of the AST product architecture is defined.

6. If, as a result of the resulting set of components and the generated list of design work to adapt the selected precedent to the s component of the i-level AST product architecture, and for cases of development of a new i-level s component of the AST product architecture, the multi-level AST product

architecture is not fully formed, then proceed to stage 3 and continue searching for precedents in PB for the next $(s+1)$ component of the AST product.

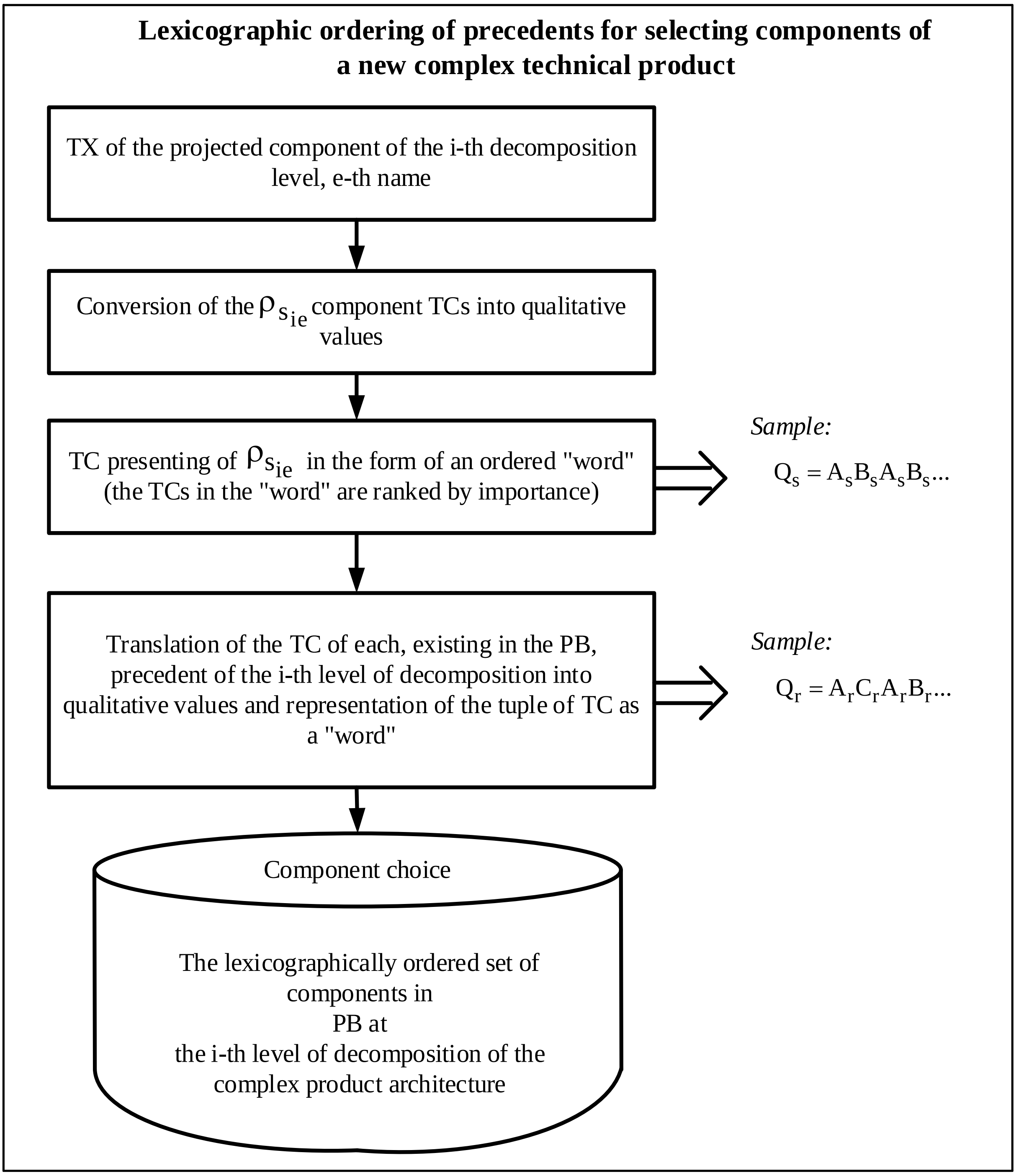

Fig. 3. Scheme of lexicographic ordering in the hierarchical precedent base to form a multilevel component architecture of the AST product

7. If the multi-level AST product architecture is fully formed, then the next step is to determine the degree of novelty of the components composition of the formed architecture.

8. The final step is to assess the design risk in the creation of a new AST product, which depends on the presence of innovative components in the AST product.

The described method of system synthesis of multilevel technical system architecture allows to form a new AST product architecture component by component by consecutive consideration of AST product decomposition levels, at that the experience of successful development of AST products is actively used. The method takes into account, while searching for the required components, the similarity (proximity) in specific values of technical characteristics, and also considers the importance of individual characteristics. In addition, the system synthesis method uses lexicographic ordering of component technical characteristics (precedents), which allows to consider the importance of each TS requirement to the designed component, regardless of how the requirements are presented, either in the form of qualitative or quantitative values.

Estimating the cost of adapting components from past designs to create a new product

The incomplete correspondence between the characteristics of the reuse component and the characteristics of the designed component in the AST product leads to the necessity of RUC adaptation. In this case, it is necessary to estimate the amount of allocated funds and the duration of work on the adaptation. Since the problem is multivariate in nature, we will use integer (Boolean) programming to find rational solutions.

Let's introduce a Boolean variable $\tau_{k_{iej}}$:

$$\tau_{k_{ie}} = \begin{cases} 1, & \textit{if for } \rho_s\textit{-th component} \\ & i\textit{-th decomposition level} \\ & e\textit{-th name} \\ & \textit{the component } \rho_{k_{ie}} \textit{ of PB is chosen;} \\ 0, & \textit{if not.} \end{cases} \tag{16}$$

Then the costs related to the adaptation of the selected component ρ_k of PB to the requirements of the designed ρ_s:

$$P_{s_{ie}} = \sum_k \tau_{k_{ie}} \cdot \omega_{k_{ie}}, \tag{17}$$

where $\omega_{k_{ie}}$ – the cost of adapting (upgrading) the k-th component of the e-th name of the i-th level of PB.

In this case, the time required to adapt (upgrade) the component ρ_k to the requirements of the designed component ρ_s:

$$T_{s_{ie}} = \sum_k \tau_{k_{ie}} \cdot t_{k_{ie}}, \tag{18}$$

where $t_{k_{ie}}$ – time spent on the modernization of the k-th component of the e-th item of the i-th level.

A natural limitation is:

$$\sum_k \tau_{k_{ie}} = 1. \tag{19}$$

It is necessary to find $\min P_{s_{ie}}$, taking into account the limitations $\hat{P}_{s_{ie}}$ associated with the allowable costs and design terms $T_{s_{ie}} \le \hat{T}_{s_{ie}}$. It should be noted that the estimation of the values of the indicators (cost $\omega_{k_{ie}}$ and time $t_{k_{ie}}$ required to adapt (modernize) the component ρ_k to the designed component ρ_s) obtained with the help of experts may not always give unbiased results. Therefore, let us consider the following model for estimating the costs (used resources): cost and time for adaptation of RUC and development of new components. The model is based on the application of different types of metrics and calculation of the degree of similarity between the designed component and the precedent taken from PB.

To determine the degree of similarity between components and precedents at different levels of the hierarchy, the nearest neighbour method can be used. The method consists in finding the degree of similarity (proximity) between the selected precedent ρ_k and the designed component ρ_s. The value of the degree of similarity is calculated by the formula:

$$SIM = \left(1 - \frac{d}{d_{\max}}\right), \tag{20}$$

where d is the calculated by the given metric «distance» between the designed component $\rho_{s_{ie}}$ and precedent $\rho_{k_{ie}}$ (RUC). Here $d_{\max}$ – maximum «distance» between existing precedents in PB of the i-th decomposition level of the e-th name.

The selected precedent $\rho_{k_{ie}}$ in PB has specific TC values. When calculating cost $\omega_{k_{ie}}$ and time $t_{k_{ie}}$, the designer may not use information about all of the technical requirements for a component $\rho_{s_{ie}}$ to be designed, but may consider in the calculations only those requirements that are fundamentally important in the design process. The importance of component requirements is indicated by importance coefficients λ_s^b, which are set by experts. In this case $\sum_{b=1}^{f} \lambda^b = 1$, where f is the number of (requirements) characteristics of the component being designed (adapted). Importance coefficients must be taken into account in cost $\omega_{k_{ie}}$ and time $t_{k_{ie}}$ estimates.

The technical requirements for the components of the AST product being created can be specified in one of four forms: as a specific numerical (point) value, as a lower limit, an upper limit, and, as a range of values.

An important point in calculating the degree of similarity between the precedent $\rho_{k_{ie}}$ and the designed component $\rho_{s_{ie}}$ is the choice of a metric for assessing proximity. It should be noted that, most of the components of different levels of the product hierarchy have quantitative characteristics. Therefore, a particular case of the Minkowski family of metrics in the form of the well-known Euclidean distance can be used to estimate the measure of proximity of components:

$$d_{ks} = \sqrt{\sum_{b=1}^{f} \left(\lambda_s^b \cdot W_{ks}^b \right)^2}, \qquad (21)$$

where d_{ks} – a measure of the proximity between the values of the precedent k characteristics and the characteristics of the designed component s;

b – ordinal number of characteristics.

Note that W_{ks}^b is determined depending on the way the requirements for the designed component s are specified. If the technical requirements for a designed component s are specified as a specific numerical (point) value, then:

$$W_{ks}^b = x_k^b - x_s^b, \qquad (22)$$

where x_s^b – characteristic value b of the designed component s;

x_k^b – characteristic value b of the precedent k, chosen from PB.

If the requirements are set in the form of a lower constraint, then W_{ks}^b is calculated by formula (23), and $G = \left[\varepsilon_s^b, \infty \right)$:

$$W_{ks}^b = \begin{cases} 0, \; x_k^b \in G, \\ \varepsilon_s^b - x_k^b, \; x_k^b \notin G, \end{cases} \qquad (23)$$

where ε_s^b – is the lower limitation for the characteristic b of the component s;

G is a set of admissible values due to the specified requirements for the performance values of the designed component of the AST product.

If the technical requirements are set in the form of an upper limit, then $G = \left(-\infty, \gamma_s^b\right]$, and W_{ks}^b is calculated by the formula

$$W_{ks}^b = \begin{cases} 0, \ x_k^b \in G, \\ x_k^b - \gamma_s^b, \ x_k^b \notin G, \end{cases} \tag{24}$$

where γ_s^b – upper limit of the characteristic b of the component s.

If the requirements are specified as a range of values and the value of the precedent characteristic falls within the specified range, then you can say that the value of the precedent characteristic and the requirement for the component of the designed product coincide. If the value of the precedent characteristic does not fall within the specified range, then the distance between the closest boundary of the range is determined. In this case $G = \left[x1_s^b, x2_s^b\right]$:

$$W_{ks}^b = \begin{cases} 0, \ x_k^b \in G, \\ x1_s^b - x_k^b, \ x_k^b < x1_s^b, \\ x_k^b - x2_s^b, \ x_k^b > x2_s^b, \end{cases} \tag{25}$$

where $x1_s^b, x2_s^b$ – limits of the value range (lower and upper) of the characteristic b of the designed component s.

In the real practice of AST creation the characteristics of some components can be mixed (quantitative and qualitative). In this case, a modification of the distance proposed by Zhuravlev can be used to determine the distance between the qualitative characteristics of the components:

$$W_{ks}^b = \begin{cases} 0, \ x_k^b \in G \\ 1, \ x_k^b \notin G \end{cases}. \tag{26}$$

In this case, G represents the specified requirements for the qualitative characteristics. These can be both values and constraints, as well as a certain range (or set) of values of the characteristics.

The resulting degree of similarity between the AST component ρ_s of the product being created and the precedent ρ_k allows to determine the cost $\omega_{k_{ie}}$ and time $t_{k_{ie}}$ required to adapt the precedent k.

The cost of adapting $\omega_{k_{ie}}$ a precedent k is calculated by the formula

$$\omega_{k_{ie}} = \begin{cases} \mu \cdot \omega_{k_{ie}}^{des}, \ if \ 1 \geq SIM_{ks} \geq \sigma, \\ \eta \cdot \omega_{k_{ie}}^{des}, \ if \ \sigma > SIM_{ks} \geq \theta, \\ \omega_{s_{ie}}^{des}, \quad if \ \theta > SIM_{ks} \geq 0, \end{cases} \tag{27}$$

where $\omega_{s_{ie}}^{des}$ – estimated by experts cost of development (adaptation) of the designed component ρ_s;

$\omega_{k_{ie}}^{des}$ – the known development cost of the chosen ρ_k -th precedent (RUC).

In this case the restrictions are satisfied: $\mu < 1,\ \eta < 1,\ \mu < \eta,\ \sigma < 1,\ \sigma > \theta,$ $\theta > 0$. $\sigma < 1,\ \sigma > \theta,\ \theta > 0$, which represent the limits of the range and are set by experts or the designer. Depending on the getting *SIM* in one or another range, the values of the coefficients $\mu < 1,\ \eta < 1,\ \mu < \eta$, determining the preliminary cost and time of adapting the selected precedent to the designed component are determined.

Time required for development (adaptation) $t_{k_{ie}}$ of the precedent ρ_k is calculated by the formula:

$$t_{k_{ie}} = \begin{cases} \mu \cdot t_{k_{ie}}^{des}, \ if \ 1 \geq SIM_{ks} \geq \sigma, \\ \eta \cdot t_{k_{ie}}^{des}, \ if \ \sigma > SIM_{ks} \geq \theta, \\ t_{s_{ie}}^{des}, \quad if \ \theta > SIM_{ks} \geq 0, \end{cases} \tag{28}$$

where $t_{s_{ie}}^{des}$ – time, in the form of expert evaluation, required to develop (adapt) the designed component ρ_s;

$t_{k_{ie}}^{des}$ – the known time spent on the development of the selected in PB precedent ρ_k.

Risk Analysis in Aerospace Technique

Risks in projects of technical systems development

Because of the complexity of the AST product design, various types of uncertainties that affect the success of product creation must be considered during the initial stages of design.

Uncertainty leads to AST product risk, which depends on the external and internal conditions of product development and the correctness of the design decisions made at all stages of the product development life cycle.

The process of creating an AST product is subject to the influence of a number of random factors due to its complexity and scale. Thus, the creation of a new AST product is carried out under the negative impact of groups of risk-forming factors that lead to the manifestation of various types of risks [27].

Risk in technique design tasks is often understood as the possibility of the occurrence of adverse events that can lead to material, time, financial and other losses, as well as failures and stoppages in the process of creating a complex AST product.

Multifaceted representation of risk is connected with a variety of risk forming factors. There is a set of integral risk forming factors, which, unlike those influencing only a specific type of risk, have an integral influence on several types of risks at once. The presence of at least one integral factor in a group of risk-forming factors is the basis for a comprehensive analysis of all types of risks associated with it.

Hence, in the early stages of AST product development it is necessary to conduct a risk study and project risk assessment, identifying the influencing risk factors with respect to their importance, and assessing the possible negative impact of risk on the achievement of the required results of the AST product development project. During the conceptualization phase of a project, a risk assessment can be used to decide whether the development should begin and whether it will be successful. Risk assessment is often understood as the process of risk identification, risk analysis, and risk level assessment [28, 29].

Risk analysis is the process of determining the sources and quantifying the level of risk.

Risk assessment is the process of comparing the results of risk analysis with established risk criteria to determine whether risks are acceptable or tolerable.

Risk level is the magnitude of a risk or combination of risks, expressed as a combination of consequences and their possibility of occurrence.

It may be noted that there is considerable uncertainty associated with risk assessment. Risk identification involves comparing quantitative risk values to risk criteria in order to determine the significance of the level of risk and the type of risk. The simplest way to determine the risk criteria involves setting a level of risk that separates the risks that need to be considered from those that can be considered non-significant. The following approaches are used to quantify risk:

1. The use of accumulated data to identify events or situations that have occurred in the past, which makes it possible to extrapolate the probability,

and therefore the risk, of their occurrence in the future. The data used must be appropriate to the type of system, equipment, organization or activity under consideration, as well as the standards of operation of the organization in question. If, in the past, the risk has occurred very rarely, then any estimate of probability will be highly uncertain and inaccurate. This is especially true when an event, situation, or circumstance has never occurred in the past, making it impossible to conclude that it will occur in the future.

2. Probability, and therefore risk, is predicted using specific techniques, such as fault tree analysis or event tree analysis. If accumulated data are not available or are not reliable, an assessment of probability as well as risk should be obtained by analyzing the system, activity, equipment or organization and its associated possible failures or malfunctioning states. Quantitative data relating to equipment, personnel, organizations, and systems obtained from experience or published data sources are then combined to arrive at a final estimate of the probability of the final event. In applying predictive engineerings, it is important in the analysis that due consideration be given to the possibility of a common failure occurring when several different parts or components of a system fail together due to a single cause. Modeling engineerings based on uncertainty effects can be used to determine the probability as well as the risk of equipment and design failure due to aging and degradation processes.

3. To quantify the probability, and hence the risk, of a fairly well-known process, expert judgments can be applied. At the same time, expert judgments should be based on all available information, including accumulated experimental and design information, as well as information specific to a particular system or organization.

It should be noted that risks are often complex especially in complex technical systems such as AST products. In this case, it is appropriate to assess the risk of the entire system as a whole, rather than for each component individually. Understanding the complexity and contribution of an individual risk to the overall or aggregate risk is important for selecting the appropriate risk assessment method or methodologies [30, 31].

Risks in aerospace technique component design

The subsection presents a risk-oriented approach in project management of complex aerospace technique. To form AST architecture, reuse components as well as «new» innovative components are actively used, the concept of «new» risk is introduced and its assessment is carried out.

The design of complex AST products often uses components that have proven themselves in previous designs and can therefore be brought into new designs through adaptation and modification. For this purpose, design organizations create design teams to develop reusable components (RUC), unify, adapt, and modify them for new projects. The risk associated with the use of «new» innovative components in AST projects depends on how effectively and in what quantity the ICs are brought into the project to create a new AST product. Hence, the relevance of the problem of analyzing innovation risk in AST design using the component architecture of the AST product.

Let us conduct a multivariate analysis of AST products created using RUC and IR with a risk-oriented evaluation of each option.

AST's component-oriented architecture, parallelism and asynchrony in performing complex functional tasks, versatility and specialization of the components used, leads to the fact that functions can be performed by individual components in a variety of ways, which leads to multivariation. Therefore, it becomes difficult to analyze and compare a large number of variants of the developed AST product manually. Therefore, the challenge arises to investigate the multitude of possible variants of component-based AST product architecture using RUC and innovative components to assess the risk of creating new AST products.

Consider the multi-level component architecture of an AST. Suppose that at the initial stage of creation the number of AST component architecture levels is defined and the condition is fulfilled $r_1 \le r_2 \le ... \le r_Q$, where r_i maximum possible number of components on the i-th level $i = \overline{1,Q}$. For the initial stages of AST product design it is possible to represent the composition of the lower Q-level components (usually they are represented as RUC). Let us denote this fact by $r_Q = n_Q$, where $n_Q = \left|B^Q\right|$, B^Q – the set of initial components of the Q-th level of specification of the AST product:

$$\sum_{\mu Q=1}^{l_Q} P_{\mu Q} = n_Q , \qquad (29)$$

where $P_{\mu Q}$ – the number of components of the μ-type of Q-level.

Components of the $(Q-1)$-th level are formed from elements of the Q-th level by mapping the set B^Q to R^{Q-1}, where R^{Q-1} is the set of «places» (nodes, blocks) in the component AST architecture, corresponding components of the $(Q-1)$-th level, $r_{Q-1} = \left|R^{Q-1}\right|$.

Therefore, the set of possible compositions of components of the $(Q-1)$-th level AST product architecture is the set of all mappings B^Q to R^{Q-1}.

By conducting sequentially from level to level the process of mappings of the set of i-th level components to the set of $(i-1)$-th level components, we obtain a set of architectural solutions of AST product for all levels of detail. It is possible to use readymade components (RUC) not only on the lower Q-th level. Therefore, it is necessary to consider the availability of these components for the i-th level:

$$r_i = r_i^{'} + n_i, \qquad (30)$$

where n_i – the number of ready-to-use components (RUC) of the level i;

$r_i^{'}$ – the number of combined i-th level components, which are formed by combining components (IC and RUC) from $i+1, i+2, ...$ levels of AST product architecture.

Consider the decomposition of the AST product architecture. Let the configuration of structural links between components at each level of detail of the AST product be known. Let us represent these links in the form of graph $G^i, i=\overline{1,Q}$, which is a union of subgraphs:

$$G^i = \bigcup_{ji} G_{ji}^i, \qquad (31)$$

where G_{ji}^i is a subgraph j of the level i.

The composition of the components is set at the level Q. It is necessary to get all variants of the multilevel component architecture of the AST product.

Let us map the set of elements B^Q into the set of vertices of graph G^Q so that each vertex of the graph has one element of the set B^Q. The set of such mappings defines the set of variants of structure T^Q for Q-th level of product decomposition AST. As the result we obtain the set of labeled subgraphs M_{B^Q}, for each variant of mappings $t_{B^Q} \in T^Q$. Then we map the set of vertices of graph G^{Q-1} into the set M_{B^Q} for all t_{B^Q}. By consequently mapping the set of elements into the set of vertices of the structure graph from level to level we get all variants of multi-level AST product architecture.

It is possible to have sets of initial elements, from which AST components are formed, at several levels of detail. Therefore, the mappings should take into account the sets of labeled subgraphs M_{B^i} and the set of initial components B^i, $i=\overline{1,Q}$.

Componenting is a mandatory attribute of AST product architecture. The componentization ensures unification and standardization in the construction of the multi-level AST product architecture, and this in turn allows for expansion and redesign into new subject areas of use. Because of the different types of components in AST product architecture, the designer has to deal with many possible AST product synthesis options in the design process.

Let the AST product architecture be formed by combining components into subsystems (SSs) and SPs into ASTs. To assess the risk of creating an AST product, the set of subsystems will be decomposed into three types:

1. Reusable, which are used without modification (RUC);

2. Subsystems that need to be modified and adapted as part of a specific AST product creation project (MCP);

3. New innovative subsystems that need to be developed (IS).

Based on expert opinions, as well as experience in creating individual components, the risk of creating an AST product can be assessed, taking into account the following particular risks:

α_1 – the risk associated with the use of RUC. Since it is minimal, we can assume that $\alpha_1 \to 0$.

α_2 – the risk associated with the modification of the RUC and the use of the MRUC. In this case, it can be considered to be in the range of $0 < \alpha_2 \le 0,5$.

α_3 – the risk associated with the creation and use of IS components. We will assume that it is maximum and is in the range of $0,5 \le \alpha_3 < 1$.

The probability of successful creation of each type of component, taking into account the types of risk presented above, can be estimated as follows:

$$\begin{aligned} P_{\alpha_1} &= 1 - \alpha_1, \quad \left(P_{\alpha_1} \to 1\right), \\ P_{\alpha_2} &= 1 - \alpha_2, \quad \left(0,5 \le P_{\alpha_2} < 1\right), \\ P_{\alpha_3} &= 1 - \alpha_3, \quad \left(0 < P_{\alpha_3} \le 0,5\right). \end{aligned} \tag{32}$$

For the success of the project to create j-th AST subsystem, consisting of n_j different components, it is necessary to obtain a probability estimate in the form of

$$P_j = P_{j_1} \cdot P_{j_2} \cdot \ldots \cdot P_{n_j} = \prod_{k_j=1}^{n_j} P_{k_j}, \tag{33}$$

where $P_{k_j} \in \left(P_{\alpha_1}, P_{\alpha_2}, P_{\alpha_3}\right)$, $k_j = \overline{1, n_j}$.

In addition to assessing the risk associated with the use of different types of components in the project, let us introduce the risk associated with the processes of integration and bundling of components in the creation of each j-th subsystem – $\alpha_{\sum j}$. As we found out, its value depends on the extent to which different types of components (RUC, MCP, IS) are used in the creation of AST product, as well as on the total number of components n_j in a subsystem. Therefore, the probability of successful creation of the j-th subsystem (SS) is: $P_{\sum j} = 1 - \alpha_{\sum j}$.

Then the probability of successful creation of the j-th AST subsystem, consisting of n_j modules, taking into account the evaluation of integration and bundling of components:

$$P_j^* = P_{\sum j} \cdot P_j = P_{\sum j} \prod_{k_j=1}^{n_j} P_{k_j}. \tag{34}$$

Final probability of successful creation of AST product (feasibility assessment) from r subsystems, taking into account their integration and bundling into the system:

$$\begin{gathered} P_{CKT} = P_{S_r} \cdot P_1^* \cdot P_2^* \cdot \ldots \cdot P_r^* = P_{S_r} P_{\sum n_1} \prod_{k_1=1}^{n_1} P_{k_1} \times \\ \times P_{\sum n_2} \prod_{k_2=1}^{n_2} P_{k_2} \times \ldots \times P_{\sum n_r} \prod_{k_r=1}^{n_r} P_{k_r} = P_{S_r} \prod_{j=1}^{r} \left(P_{n_j} \prod_{k_j=1}^{n_j} P_{k_j} \right), \end{gathered} \tag{35}$$

where P_{S_r} – probability of integrating r subsystems into the system (product AST).

Project risk assessment, taking into account the degree of novelty of the components

Design risk strongly depends on the degree of novelty of the components of the created AST product. Therefore, to assess the risk, the components of the synthesized structure were divided into three groups: reusable, modifiable (adaptable), and innovative components. Thus, the work on the creation of a new AST product includes the design work on the development of new components, the acquisition of RUC, and work on the modification and adaptation of RUC.

Project risk can lead to an adverse event for the project to create a new AST product, the occurrence of which leads to a halt of the project. Therefore, the project risk will be associated with the fact that during the design work on the creation of a new AST product the result will not be obtained in accordance with the requirements of the technical task.

As noted earlier, the assessment of design risk in the early stages of the creation of a technical system is one of the relevant tasks in the creation of a new AST product, the result of risk assessment determines the feasibility of further product development. That is why it is so important in the early stages of technical system development to synthesize the architecture based on the joint application of the component approach and the use of positive experience of past developments, which will ensure the reduction of design risk on the creation of a new AST product.

When assessing the possible risks of creating AST products, it is necessary to take into account the fact that some types of risks, such as operational risk, are difficult to formalize and quantify, which is associated with the presence of the «human» factor.

It is important for design risk assessment to obtain a quantitative or qualitative assessment of the degree of novelty and innovativeness of the components of the AST product being created. The degree of novelty can reduce or even «neutralize» the negative impact of risks at the initial stage of AST product creation.

To study the risk of design work on the creation and adaptation of AST product components, taking into account the degree of novelty of the components, it is advisable to use methods of fuzzy sets theory for qualitative assessments, involving expert evaluations [32 – 34].

The theory of fuzzy sets (fuzzy logic) is successfully used, nowadays, in risk management processes. With the lack of statistical information fuzzy sets theory is an alternative to probabilistic methods and allows to use both quantitative and qualitative characteristics to evaluate parameters, as well as to analyze heterogeneous and insufficient volume of statistical samples, which is an advantage in conditions of scarcity or high cost in obtaining information.

To assess the risk based on the degree of novelty of the components of the structure of a technical product, it is reasonable to use linguistic variables. The concept of a linguistic variable is used when describing objects and phenomena using fuzzy sets.

Fuzzy variables that will be used to assess the novelty of components of AST products can be defined using the triplet $<\alpha, U, A>$, where α is the name of the variable; U – universal set (definition area α); A – fuzzy set on U, which describes the restrictions on the values of the fuzzy variable α; u – common name (the same for all elements of the set U).

The linguistic variable is represented as a set $< V, T, U, G, M >$, where V is the name of the linguistic variable; T is the set of values (term set) of the linguistic variable, which are the names of fuzzy variables, each of which is defined in the set U ; $T = V_1, V_2, ..., V_f, ..., V_{k,}$ $f = 1..k$; k is the number of values of the linguistic variable; U is a universal set, reflecting the values of the linguistic variable.

Each value (term) V_f of a linguistic variable V must be mapped to a fuzzy subset of the universal set U given by the corresponding membership function $\mu_{V_f}(u), u \in U$. The value area of any membership function lies on the interval $[0;1]$; G is a syntactic procedure allowing to operate with elements of a term set T , in particular, to generate new terms (values) of a linguistic variable; M is a semantic procedure allowing to turn each new value of a linguistic variable generated by procedure G into a fuzzy variable, i.e. to form a corresponding fuzzy set.

To analyze the risk of design work and the level of risk, it is reasonable to estimate the degree of novelty of the components of the new product AST, which will affect the probability of the manifestation of risk factors, which can be represented in the form of linguistic variables. In this case, the values of each of these linguistic variables should be presented in the form of corresponding fuzzy values using the generally accepted and frequently used triangular membership function.

The triangular representation in the fuzzy number transformation is often used in economic analysis as well as in risk management processes. This is due to the fact that, when analyzing the properties of nonlinear operations using fuzzy representations, the form of the membership function is close to the triangular. In addition, the selection of three significant points of the initial data is quite often used in investment analysis. To these points the qualitative values of probability of realization of the corresponding («pessimistic», «normal», «optimistic») scenarios are compared.

To assess design risk using fuzzy representations in the initial stages of building a complex AST product, the following steps should be implemented:

Step 1: The first step in assessing design risk in the initial stages of building an AST product is to identify the risks and identify the risk-creating factors. To do this, it is necessary to identify the basic risk groups, as well as intra-group risk factors contributing to the occurrence of a particular type of risk and related to the basic risk group $x_1,\ x_2,\ ...,\ x_n,\ j = 1..n$.

Step 2. It is necessary to form a preliminary composition of the design work on the creation of the AST product. Design work should include design work on the adaptation of RUC, design work on the acquisition of RUC, as well as design work on the creation of new IS. The purchase of ready-made RUCs for the creation of the AST product in the domestic or foreign markets can reduce the cost of product development.

Step 3. Setting the values of linguistic variables to estimate the risk level of factor *r* and the importance of risk factor *s* using a triangular identity function.

Analytically, the triangular membership function can be represented as follows:

$$\mu_{V_f}(u)=\begin{cases}0;\ u\le a,\\ \dfrac{u-a}{b-a};\ a\le u\le b,\\ \dfrac{c-u}{c-b};\ b\le u\le c,\\ 0;\ u\le c\end{cases} \quad (36)$$

where $(a,\ c)$ – range of triangular fuzzy number values;

b – the mode of a triangular fuzzy number.

The same form has the identical membership functions for $\mu_{V_f}(r)$ and $\mu_{V_f}(s)$.

Next, the scale of correspondence of linguistic variables to fuzzy numbers is constructed (table 1).

Table 1

Scale of correspondence of linguistic variables to fuzzy numbers

Number of the linguistic variable value	Values of the linguistic variables describing the risk level of a factor (r) and the importance level of a factor (s)	Fuzzy triangular numbers N, representing the value of the linguistic variables of factor risk level (r) and factor importance level (s)
1	$r^1;\ s^1$	$N_{r^1};\ N_{s^1}$
…	…	…
i	$r^i;\ s^i$	$N_{r^i};\ N_{s^i}$
…	…	…
k	$r^k;\ s^k$	$N_{r^k};\ N_{s^k}$

where N_s, N_r – fuzzy numbers representing, respectively, the values of the linguistic variables of importance and risk factor level; i – number of the linguistic variable value $(i=1...k)$; k – the number of linguistic variables describing the importance of the risk factor *s* and its level r.

Then the linguistic variables s and r are replaced by fuzzy numbers N_s and N_r.

Step 4. The importance of risk-forming factors s_j is assessed on the basis of a preliminary classification of the design work, based on the degree of novelty of the ACP product components.

The degree of novelty of the new product components will affect the importance of the risk-forming factor s_j:

$$\begin{bmatrix} s_{1\text{RUC}} & s_{j\text{RUC}} & \cdots s_{n\text{RUC}} \\ s_{1\text{MRUC}} & s_{j\text{MRUC}} & \cdots s_{n\text{MRUC}} \\ s_{1\text{IC}} & s_{j\text{IC}} & \cdots s_{n\text{IC}} \end{bmatrix}, \quad (37)$$

where $s_{\text{j RUC}}$ – linguistic assessment of the importance of the risk factor j, associated with a separate group of project work on the acquisition of the reuse component; $s_{\text{j MRUC}}$ – linguistic assessment of the importance of the risk-forming factor j, for the group of works on the adaptation of RUC; $s_{\text{j IC}}$ – linguistic assessment of the importance of the risk-forming factor j, for a group of design work on the creation of new components.

As suggested earlier, design works are divided into three groups, depending on the degree of novelty of the designed components: design works to adapt MRUC, design works to acquire RUC, and design works to create new IS. We will assume that the linguistic value of the importance variable of all risk factors for the group of design works on the acquisition of RUC will be approximately the same. Note that, the works in this group are most sensitive to external, economic risks associated with orders and their fulfillment or the acquisition of components of AST, and less sensitive to scientific and technical risks, since the components have already been created. The third group of works is associated with the novelty and uniqueness of the created AST product and is most exposed to risk factors of scientific and technical nature. Works of the second group related to modification and adaptation of MRUC are subject to moderate influence of all risk factors.

Step 5. Assessment of each risk factor r_j.

For each identified risk-creating factor, the probability of the risk factor and its possible impact must be assessed.

For an estimation of a level of each risk forming factor r_j we will use a matrix of probability and consequences. The matrix of probability and consequences is made on the basis of results of polls and expert evaluations, by establishing the connection between probability and impact of risk forming factor. Using this matrix, risk factors can be prioritized according to the potential degree of significance of their consequences for the feasibility of the AST product development project.

At the intersection of rows and columns of the matrix of probability and consequences we put down estimates of values of risk levels of the factor r_j. Factor r_j risk levels are set based on the peculiarities of each risk-forming factor. The value of the risk level of a factor r_j depends on the nature of the risk-forming factor.

Step 6. Since r_j and s_{jt} (where t is a group of design work, depending on the degree of novelty of the components, $t \in \{\mathrm{RUC}, \mathrm{MRUC}, \mathrm{IC}\}$) and can be represented in the form of values of linguistic variables, using fuzzy values, so it is necessary to carry out the procedure of dephasing (elimination of fuzzy).

The impact of risk on subsequent design work is determined by two main characteristics: the degree of novelty of the components of the designed product and the risk level of each risk-forming factor.

To assess the design risk at the initial stages of system development, it is necessary to create a matrix, the rows of which are the design activities, and the columns are the risk-forming factors. At the intersection of line and column of the matrix, the value $g_{jtw}\left(r_j, s_{jt}\right)$, which represents the level of risk of each factor r_j, taking into account its importance s_{jt}, depending on the works, grouped by the criterion of the degree of novelty of the product components AST; w – number of design work.

Operations with triangular numbers are reduced to operations with abscissas of vertices of membership functions:

$$\left(a_1, b_1, c_1\right) \cdot \left(a_2, b_2, c_2\right) \equiv \left(a_1 \cdot a_2, b_1 \cdot b_2, c_1 \cdot c_2\right) \tag{38}$$

Calculations to eliminate fuzziness are performed using the well-known centroid defuzzification method, which is related to the notion of «center of gravity» [35]:

$$g\left(r, s\right) = \frac{\int_a^c u \cdot \mu_{N_r \cdot N_s}\left(u\right) du}{\int_a^c \mu_{N_r \cdot N_s}\left(u\right) du}, \tag{39}$$

where $\mu_{N_r \cdot N_s}\left(u\right)$ – the membership function of the product of fuzzy numbers N_r and N_s; N_r, N_s – fuzzy numbers representing the values of the linguistic variables of risk levels and importance of risk factors, respectively; $\left(a,\ c\right)$ – the range of values of the triangular fuzzy number.

As a result, we get a matrix of values $g_{jtw}\left(r_j, s_{jt}\right)$, which is formed using formulas (36), (38), (39).

To simplify the calculations, it is advisable to define in advance a matrix for all values of $g(r,s)$, which contains all possible intersections of the risk level of each factor r_j and the importance of the risk-forming factor s_j.

It is possible to use the method of calculating the risk assessment, which is proposed in the works, where the importance of risk is assessed by expert judgment. The essential difference of this method is that the value s_{jt} is determined based on the degree of novelty of the groups of design works related to the components of the created AST product.

Step 7. Definition of a fuzzy matrix H of intersections of risk levels of factors, taking into account their importance and accessory functions of triangular numbers for each of the project works W_{it}. The intersection of an accessory function with a fuzzy number yields a pair of values, which are commonly referred to as confidence interval bounds.

The fuzzy matrix is defined by intersecting each value of the matrix obtained in step 6, $g_{jtw}\left(r_j, s_{jt}\right)$ with the accessory functions of the triangular numbers $\mu_{V_\varphi}(u)$ and $\mu_{V_{\varphi+1}}(u)$, where $\varphi = 1, 2, ..., k-1$. Thus:

$$h\left(g_{jtw}\left(r_j, s_{jt}\right), V_{\varphi+1}\right) = 1 - h\left(g_{jtw}\left(r_j, s_{jt}\right), V_\varphi\right),$$

$$h\left(g_{jtw}\left(r_j, s_{jt}\right), V_f\right) = 0,$$

at $\forall f$, $f \neq \varphi$, $f \neq \varphi + 1$.

Fuzzy matrix H has the form:

$$H = \begin{bmatrix} h\left(g_{1t1}(r_1, s_{1t}), V_1\right) \quad h\left(g_{1t1}(r_1, s_{1t}), V_2\right) ... h\left(g_{1t1}(r_1, s_{1t}), V_k\right) \\ h\left(g_{2t1}(r_2, s_{2t}), V_1\right) \quad h\left(g_{2t1}(r_2, s_{2t}), V_2\right) ... h\left(g_{2t1}(r_2, s_{2t}), V_k\right) \\ \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots \\ h\left(g_{1t2}(r_1, s_{1t}), V_1\right) \quad h\left(g_{1t2}(r_1, s_{1t}), V_2\right) ... h\left(g_{1t2}(r_1, s_{1t}), V_k\right) \\ \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots \\ h\left(g_{jtw}\left(r_j, s_{jt}\right), V_1\right) \quad h\left(g_{jtw}\left(r_j, s_{jt}\right), V_2\right) ... h\left(g_{jtw}\left(r_j, s_{jt}\right), V_k\right) \\ \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots \\ h\left(g_{ntm}(r_n, s_{nt}), V_1\right) \quad h\left(g_{ntm}(r_n, s_{nt}), V_2\right) ... h\left(g_{ntm}(r_n, s_{nt}), V_k\right) \end{bmatrix}, \quad (40)$$

where m – total number of design works.

To reduce the number of calculations it is recommended to build in advance H' – fuzzy matrix of intersections of all possible values of risk levels of factors, taking into account their importance $g(r,s)$ with the accessory functions of triangular numbers $\mu_{V_\varphi}(u)$ and $\mu_{V_{\varphi+1}}(u)$.

Step 8. Obtaining a fuzzy risk assessment of the totality of all risk factors for each of the design work to adapt (upgrade) the MRUC or to create new components of the created product AST. Let's use the formula:

$$R_f^w = \sum_{j=1}^{n} \alpha_j \times h\Big(g_{jtw}\big(r_j, s_{jt}\big), V_f\Big)\ ,\ f = 1..k\,, \tag{41}$$

where

$$\alpha_j = \frac{1}{n \times d}\,,\ \text{accordingly,}\ \ 0 \le \alpha_j \le 1. \tag{42}$$

$w = 1..z$, z – number of design works included in the group of works on adaptation (modernization) of MRUC or on creation of IC;

d – the total number of groups of design work to adapt (upgrade) MRUC and create IC (d represents the total number of adapted or developed components that are part of the created product).

Step 9. Obtaining a fuzzy risk assessment of the totality of all risk factors for each group of project works to adapt (modernize) MRUC or to create IC $R_f^{гр}$. To do this, we will use the formula:

$$R_f^{gr} = \sum_{w=1}^{z} R_f^w\,,\ f = 1...k\,. \tag{43}$$

Step 10. Obtaining a fuzzy risk assessment for the totality of all risk factors, for all groups of project works on adaptation (modernization) of MRUC or on creation of IC R_f^{np}:

$$R_f^{pr} = \sum_{h=1}^{d} R_f^h\,,\ f = 1..k \tag{44}$$

where h – number of the group of project works on adaptation (modernization) of reuse components and creation of new components $(h = 1...d)$.

Step 11. It is necessary to calculate the centroid value $g\left(V_f\right)$ $\left(g\left(V_f\right)\right.$ – centroid of the value V_f of the linguistic variable $\left.V\right)$ using a dependency:

$$g\left(V_f\right)=\frac{\int_{a_f}^{c_f} u \cdot \mu_{V_f}(u) du}{\int_{a_f}^{c_f} \mu_{V_f}(u) du}, \; f=1..k. \tag{45}$$

Next, we assess the risk of a group of project works to adapt (modernize) MRUC or to create IC:

$$R^{gr}=\frac{\sum_{f=1}^{k} g\left(V_f\right) \times R_f^{gr}}{\sum_{f=1}^{k} R_f^{gr}}, \; f=1..k. \tag{46}$$

Subsequent assessment of the feasibility risk of a new AST product project related to the novelty of the designed product is found by eliminating the fuzzy representation using the centroid method:

$$R^{pr}=\frac{\sum_{f=1}^{k} g\left(V_f\right) \times R_f^{pr}}{\sum_{f=1}^{k} R_f^{pr}}, \; f=1..k, \tag{47}$$

where R^{np} represents the probability of obtaining a negative result that does not meet the requirements of the AST creation specification.

Thus, the proposed method of design risk assessment at the initial stages of AST product creation primarily takes into account the degree of novelty of the components of the created product, as well as the vagueness in the representation of risk-forming factors.

A distinctive feature of this method is that it is applicable to the assessment of design risk during the creation of an AST product, taking into account individual groups of design work associated with the adaptation (modernization) of MRUC or with the creation of new IC [36].

Study of feasibility of complex aerospace technique projects

Let us consider and investigate possible situations that arise in the process of creating an AST product. To do this, we will use the methods of enumeration theory [37, 38]. Let the AST product architecture be formed only from components of one kind (e.g., RUC). Let us combine the components into separate SSs. Denote the number of available components by n, and the number of subsystems built with RUC by r. Since the components are of the same kind (RUC) any permutation in the initial set B is possible. Such permutations are $n!$, so the symmetric group S_n acts on the initial set of modules. The set of modules is mapped to the set SS. Let us be interested only in the composition in AST architecture without taking into account the relations between separate SSs, so on the set SS, which we denote by R, $|R|=r$, the symmetric group S_r also acts. The maximal possible number of SSs will be in the case $n=r$.

It is necessary to estimate a set of possible variants of AST construction on the basis of RUC. This problem is equivalent to the problem of dividing the number n into no more than r parts. Then the number of variants:

$$K=\left|H_R\right|^{-1}\sum_{h\in H_R} Z\left(H_B;...;\sum_{j/i} jC_i,...\right)=\frac{1}{r!}\sum_{h\in S_r} Z\left(S_n;...;\sum_{j/i} jC_i,...\right), \qquad (48)$$

where $Z(H_B;...)$ – cycle index of the substitution group H_B.

Next, for each i-th variant of AST, consisting of r_i subsystems, which includes only RUCs, let us estimate the probability of successful creation of the system in the form of:

$$\begin{aligned} P_{AST_i,RUC} &= P_{S_{r_i}}\cdot P_{1_i}^{*}\cdot P_2^{*}\cdot\ldots\cdot P_{r_i}^{*} = \\ &= P_{S_{r_i}}\cdot P_{\sum n_{1_i}}\cdot P_{\alpha_1}^{n_{1_i}}\cdot P_{\sum n_{2_i}}\cdot P_{\alpha_1}^{n_{2_i}}\cdot\ldots\cdot P_{\sum n_{r_i}}\cdot P_{\alpha_1}^{n_{r_i}} = \qquad (49)\\ &= P_{S_{r_i}}\prod_{k_i=1}^{n_{r_i}} P_{\sum nk_i}\cdot P_{\alpha_1}^{n_{1_i}+n_{2_i}+\ldots+n_{r_i}}, \end{aligned}$$

where $P_{\sum nk_i}$ – probability of successful complexation of subsystems with the help of RUC.

Here it is necessary to consider the condition $n_{1_i}+n_{2_i}+\ldots+n_{r_i}=n$, which means that all RUC components will be used in the creation of the AST. Therefore, the probability of creating the i-th variant of the AST consisting only of RUC components:

$$P_{AST_i,RUC}=P_{S_{r_i}}\prod_{k_i=1}^{n_{r_i}} P_{\sum nk_i}\cdot P_{\alpha_1}^{n}. \qquad (50)$$

Similarly, we can estimate the probability of creating the i-th AST variant consisting only of MRUC:

$$P_{AST_i,MRUC} = P_{S_{r_i}} \prod_{k_i=1}^{n_{r_i}} P_{\sum nk_i} \cdot P_{\alpha_2}^{n}. \tag{51}$$

To create an AST that consists only of «new» IC components:

$$P_{AST_i,IC} = P_{S_{r_i}} \prod_{k_i=1}^{n_{r_i}} P_{\sum nk_i} \cdot P_{\alpha_3}^{n}. \tag{52}$$

Then let us determine the number of possible variants of the composition of AST for a given (known) number of SS, taking into account the condition $r \le n$. The action of the symmetric group S_n on the set B leads to the fact that we are interested only in the number of components. Therefore the mapping B into R can be replaced by the mapping R into the set $M = \{1, 2, ...\}$ with the restriction:

$$\sum_{k \in R} Y(K) = n, \tag{53}$$

where $Y(K)$ – shows how many components are included in the K-th SS (at least one).

Give the elements of the set M weights:

$$\varpi^1, \varpi^2, \varpi^3, ..., \tag{54}$$

and we will look for equivalence classes with weight ϖ^n:

$$Z\left(S_r; \varpi + \varpi^2 + \varpi^3 + ..., \varpi^2 + \varpi^4 + \varpi^6 + ..., ...\right). \tag{55}$$

It is necessary to find the coefficient at ϖ^n in this decomposition.

Let us consider the situation when the AST product composition is formed from three kinds of components (RUC, MRUC, IC). The total number of components

$$n = \sum_{\mu=1}^{3} P_\mu , \tag{56}$$

where P_μ – number of components of μ-th type.

In this case, on the initial set of components B the sum of symmetric groups acts:

$$H_B = S_{p_1} + S_{p_2} + S_{p_3} , \tag{57}$$

and on the set SS acts, as in the previous case, the symmetric group – S_r.

It is necessary to determine all possible variants of the AST composition. To do this, we use the following formulation associated with the enumeration of variants:

$$K = \left|H_R\right|^{-1} \sum_{h \in H_R} Z\left(H_B;\ldots\sum_{j/i} jC_j \right) = \frac{1}{r!} \sum_{h \in S_r} Z\left(S_{p_1} + S_{p_2} + S_{p_3};\ldots,\sum_{j/i} jC_j,\ldots \right). \quad (58)$$

Using this formula we can find the number of possible variants of AST composition containing *r* and less subsystems.

Determine the number of possible variants of the composition of the AST product for a given number of SS $r \le n$. Using the previous formula, we enumerate the variants of AST composition starting from the number r of SS and ending with one. If we take $r-1$ of SS, then we count the number of variants for $r-1, r-2, \ldots, 1$ of SS in the composition of AST product. In this case to determine the number of possible variants of AST composition with r-th number of SSs we should find the difference:

$$\begin{aligned} K = K_r - K_{r-1} = \frac{1}{r!} \sum_{h \in S_r} Z\left(S_{p_1} + S_{p_2} + S_{p_3};\ldots,\sum_{j/i} jC_j,\ldots \right) - \\ - \frac{1}{(r-1)!} \sum_{h \in S_{r-1}} Z\left(S_{p_1} + S_{p_2} + S_{p_3};\ldots,\sum_{j/i} jC_j,\ldots \right). \end{aligned} \quad (59)$$

Consider the case where, for each j-th subsystem, the composition is formed from components of three kinds (RUC, MRUC, IC):

$$n_j = n_{j_1} + n_{j_2} + n_{j_3} = \sum_{j_q=1}^{3} n_{j_q}, \quad (60)$$

where $0 \le n_{j_q} < n_j$.

Then the probability of successful creation of the j-th subsystem using all types of components and without taking into account the subsequent bundling:

$$P_j = P_{\alpha_1}^{n_{j1}} \cdot P_{\alpha_2}^{n_{j2}} \cdot P_{\alpha_3}^{n_{j3}}. \quad (61)$$

Taking into account the bundling of components in the j-th of the SS, the probability of successful creation is determined as follows:

$$P_j^* = P_{\sum n_j} \cdot P_{\alpha_1}^{n_{j1}} \cdot P_{\alpha_2}^{n_{j2}} \cdot P_{\alpha_3}^{n_{j3}}. \quad (62)$$

Then for the i-th possible variant of AST product creation, consisting of r_i subsystems, built on the basis of different components, the probability of successful implementation of the project to create a new AST product:

$$\begin{aligned} P_{CKT_i} &= P_{S_{r_i}} \cdot P_{\sum n_{1_i}} \cdot P_{\alpha_1}^{n_1, j_1} \cdot P_{\alpha_2}^{n_1, j_2} \cdot P_{\alpha_3}^{n_1, j_3} \times \\ &\times P_{\sum n_{r_i}} \cdot P_{\alpha_1}^{n_2, j_1} \cdot P_{\alpha_2}^{n_2, j_2} \cdot P_{\alpha_3}^{n_2, j_3} \times \ldots \\ &\times P_{\sum n_{r_i}} \cdot P_{\alpha_1}^{n_r, j_1} \cdot P_{\alpha_2}^{n_r, j_2} \cdot P_{\alpha_3}^{n_r, j_3} = \\ &= P_{S_{r_i}} \prod_{k_i=1}^{n_{r_i}} P_{\sum nk_i} \cdot P_{\alpha_1}^{n_1, j_1 + n_2, j_1 + \ldots + n_r, j_1} \times \\ &\times P_{\alpha_2}^{n_1, j_2 + n_2, j_2 + \ldots + n_r, j_2} \cdot P_{\alpha_3}^{n_1, j_3 + n_2, j_3 + \ldots + n_r, j_3}. \end{aligned} \quad (63)$$

The proposed method for assessing the probability of successful implementation of a new AST product project is reasonable to apply in the management of new aerospace equipment development projects, when developers use a component approach to the construction of the system architecture and actively use previous experience in the form of reuse components [39].

Simulation modeling of the aerospace product development life cycle

When creating new generation AST products, a lot of attention is paid to modern technologies of architecture-oriented synthesis. A study of the early stages of the life cycle (LC) of an AST product under development allows us to evaluate the results of the designers' actions to create the component architecture of an AST product at each stage of the LC. The earlier classification of components made it possible to distinguish three main types of components used in the AST product:

– reuse components (RUC);

– new innovative components (IC);

– combined (complex) components (CC), which can include RUC and IC.

When the RUC is incorporated into a new AST product under development, the RUC is upgraded, if necessary, to include refinement and adaptation. On the basis of expert opinions, as well as taking into account the experience of component creation, as was said earlier, the risk associated with the use of RUC will be minimal. At the same time, the risk value will increase depending on the depth of RUC modification.

In order to form LC taking into account the new components and their innovativeness, it is necessary to carry out a number of new works related to the fulfillment of regulatory requirements for the created AST products, including, if necessary, research, developmental work, prototype tests [40 – 42], etc.

In this case, the number of stages of design work in LC increases, which means that the risk associated with the creation of innovative components increases dramatically.

A simulation model was built to study the life cycle of component creation in AST product architecture, which is used to study the whole process of creating a complex aerospace complex.

The proposed simulation model uses event-driven way of representation of design work in LC, has different level of detail in AST product architecture representation and allows modeling main phases of LC with consideration of component architecture of the product. Let us briefly present the necessary actions of the designer taking into account the use of the developed simulation model.

In accordance with the work plans for the creation of the AST product, a general schedule is formed in which the dates for the start of work on the creation of individual components of the AST product are marked.

For each component, a description of the stages of creation in LC is formed in advance, which is further stored in the LC component library (precedent database).

For each component, a set of characteristics is described, which are further used in the simulation:

– time intervals of work for each LC phase (point estimates, interval estimates, mathematical expectation, etc. can be used);

– estimation of work success probability, which is set with the help of experts and takes into account the type of component (RUC, IC, MRUC);

– estimation of estimated time for redesigning, in case of repeated work in case of failure to perform the design work in the required time and with the required quality.

The developed LC event simulation method for creating component architecture of an AST product includes the following steps:

1. Formation of AST product component composition. Types of components and their number are defined (RUC, IC, MRUC).

2. Defining initial characteristics of components. Define time intervals of works, probabilities of their successful completion. Defines times of reperformance (lengthening of design work completion terms) in case of their unsuccessful completion.

3. Setting of deadlines for individual LC phases in accordance with the general plan-schedule for AST product creation.

4. Conducting an event simulation of the design work execution for creating components of the new AST product.

5. Generation of final simulation results. Simulation results include projected timeframes for creation of individual components and the final timeframe for creation of a new AST product.

If, for a variety of reasons, the given LC characteristics contain random factors, the simulation is repeated many times and the results are statistically averaged.

Fig. 4 shows the structure of the simulation event model. The simulation modeling system used is GPSS.

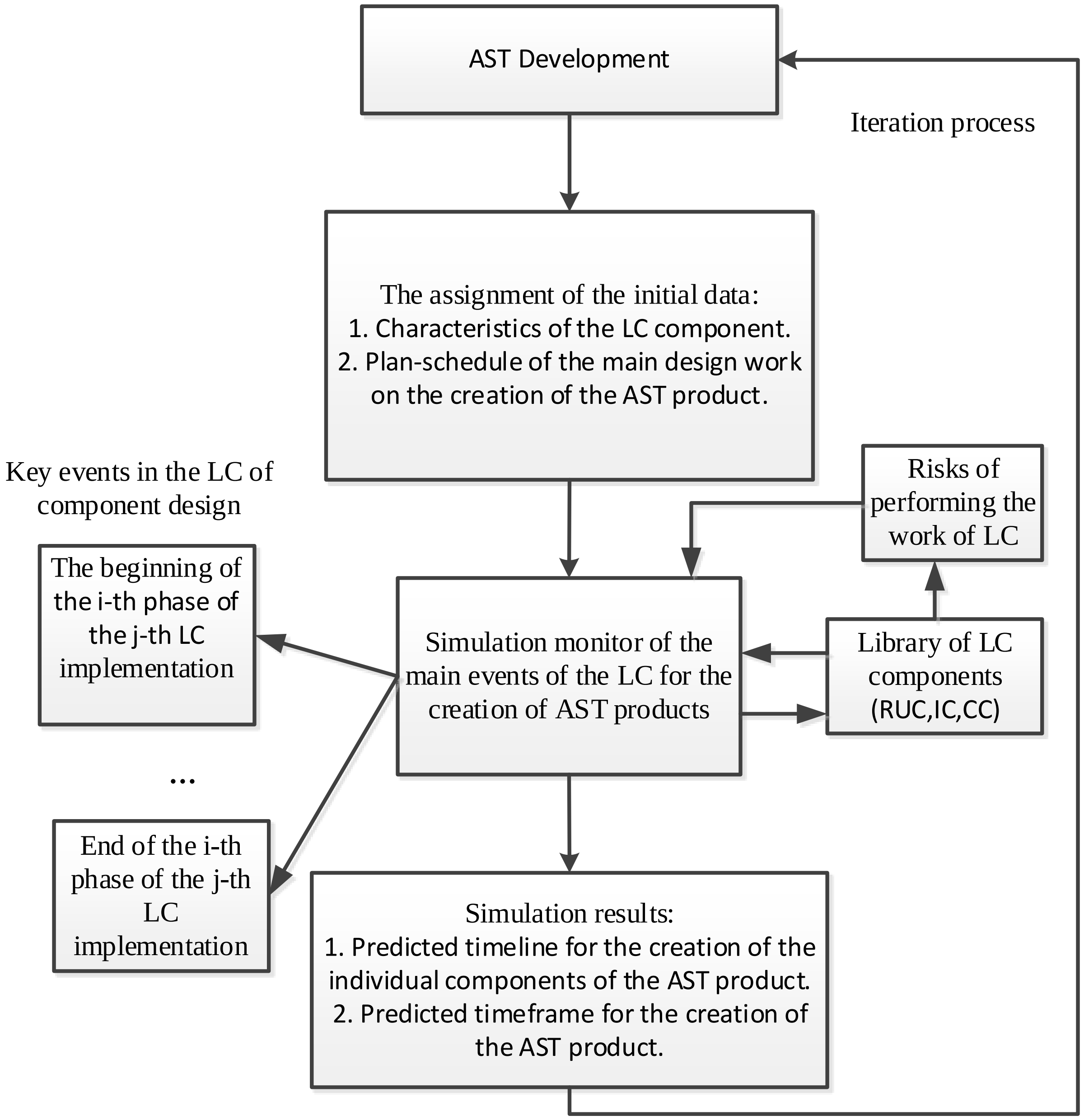

Fig. 4. Structure of the simulation event model

Conclusions

The conducted research is related to the urgent problem of creating modern, high-tech, complex technical products in conditions of limited capabilities of enterprises-developers of new aerospace equipment (AST). A new synthesis method based on architecture-oriented component design of AST is proposed. A study of the set of components included in the AST product structure was performed. Components from past developments, innovative components and complex (combined) components are identified. By combining different components and using a precedent base, a component structure of a new AST product is formed with the required characteristics of the AST creation project. A top-down design technique is used to form a multi-level component architecture for AST. Clustering of multiple components in the precedent base allows selection of required components at different levels of detail to create a multilevel AST structure. A method for the synthesis of a multilevel structure based on a sequential process of transition from a level to an adjacent lower level in a multilevel representation of the structure of the designed AST product and selection of required components from a precedent base is developed. Consideration is given to the risks in the design of a new AST product associated with the use of innovative components and the integration of components into a multi-tiered AST architecture.

The proposed methodology allows:

– to scientifically inform the formation of a multi-tiered AST architecture based on a system component representation;

– to create a new design technology, with active use of the positive experience of past AST developments;

– to reduce the time and to minimize the risks of designing new AST products.

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MISSION AND STRATEGY OF THE COMPLIANCE PROGRAM OF METALLURGICAL ENTERPRISE DEVELOPMENT MANAGEMENT

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The authors analyze the peculiarities of the macro- and micro-environment in the conditions of martial law in which Ukrainian industrial enterprises are forced to operate and directions for overcoming the crisis in the economy as a result of the war, investigate aspects of the formation of the mission and strategy of the enterprise in the conditions of the need to rebuild the Ukrainian economy and the formation of a compliance program as a tool of minimization risks and ensuring the sustainable development of metallurgical enterprises that are of strategic importance to the state. ***The object of the study*** *is the process of forming a compliance program for an industrial enterprise, in particular a metallurgical one.* ***The subject of the research*** *is theoretical approaches to defining the mission and development strategy of a metallurgical sector enterprise using a compliance program, as well as scientific views, ideas, and concepts of domestic scientists on issues of compliance implementation at domestic enterprises.****The purpose of the study*** *is modern approaches to defining the mission and strategy with the application of the compliance program as the main tool for ensuring protection against risks and maintaining the safety of the operation of the enterprise of the metallurgical sector of the economy and the directions of its further development in the Ukrainian realities in order to obtain competitive advantages and increase the efficiency of the enterprises of this sphere.****The research methodology*** *is based on scientific generalization, on the application of the dialectical method, genetic approach, scientific abstraction, theoretical provisions of system analysis, methods of economic analysis.*
The peculiarities of the formation of the compliance program are established, its main stages are formulated, attention is focused on internal audit indicators and so-called indicators of compliance with requirements and control over the achievement of these indicators based on the application of decision support systems using artificial intelligence. As a result of the study, the role, place and connections of the compliance program in the formation of the mission and strategy of the metallurgical enterprise, which are related to the need to assess and minimize risks, are determined.

Introduction

Ukraine’s economy has practically been destroyed as a result of the war, there is no doubt that victory will inevitably come, and the reconstruction of the Ukrainian state has already become the main task for all Ukrainians. In addition, it should be emphasized that the direction of movement is also determined, it is a movement towards the EU and the adoption of European values and management principles in all areas, including the economy. In such conditions, scientists and their research are capable of helping and equipping the nation with relevant theoretical and practical knowledge.

The relevance of compliance research is due to the fact that in modern conditions of the activation of innovative, scientific, technical and information activities, there is a need to build enterprises and management systems, as open systems, on the basis of compliance with certain rules, norms, standards and requirements of both the internal environment and the external environment in which the enterprise operates.

Why is it so important at this stage? Today, as a result, first – of the pandemic, and then – of the war, we are witnessing fundamental changes in the world order. Globalization is losing its value as a means of reducing costs in value chains precisely because there is a destruction of globalization relations, as a result of the struggle of democracy with authoritarian regimes. The reorientation of existing European markets and the search for new ones can mitigate this destruction, but requires the search for new missions, strategies and goals. The main value of European democracy lies in consistent work, despite all difficulties, to unify all institutions in the direction of key and fundamental aspects, such as the free movement of goods, capital and labor and technology. Therefore, compliance, from this value point of view, corresponds as closely as possible to such criteria.

Compliance with laws, regulations and standards in the area of compliance usually concerns matters such as maintaining appropriate standards of conduct in the market, managing conflicts of interest, treating clients fairly and ensuring a fair approach when advising clients. The scope of compliance also includes specific areas, such as:

– opposition to the legalization of proceeds obtained through crime and the financing of terrorism;

– development of documents and procedures that ensure compliance of the company’s activities with current legislation;

– protection of information flows, combating fraud and corruption, establishing ethical standards of employee behavior, etc. [1].

Thus, the object of the study is the process of forming a compliance program for an industrial enterprise, in particular a metallurgical enterprise.

The subject of the research is theoretical approaches to defining the mission and development strategy of a metallurgical sector enterprise using a compliance program, as well as scientific views, ideas, and concepts of domestic scientists on issues of compliance implementation at domestic enterprises.

The purpose of the study is modern approaches to defining the mission and strategy with the application of the compliance program as the main tool for ensuring protection against risks and maintaining the safety of the operation of the enterprise of the metallurgical sector of the economy and the directions of its further development in the Ukrainian realities in order to obtain competitive advantages and increase the efficiency of the enterprises of this sphere.

Such leading scientists as P. Pererva, T. Kobeleva, S. J. Griffith, A. Filippovych, V. Cherepanova, O. Nieizviestna, R. A. Posthuma, M. Mukha, O. Korobkova, M. Novikova, A. Slyusar, and others.

But the question of the role and possibilities of using artificial intelligence in decision support systems to minimize risks, in particular investment risks, has not yet been sufficiently investigated and needs to be improved.

The work of such scientists as M. Meskon, F. Khedoury, I. Ansoff, I. Druker, F. Kotler, G. Mintzberg, M. Porter, A. Thompson, J. Strickland, A. Mazaraki, V. Verba, O. Gaponenko and others.

Such domestic scientists as Yu. Proydak, K. Kovalchuk, D. Kozenkov, A. Amosha and others are devoted to the problems of the development of metallurgical enterprises.

But it is necessary to emphasize the process of forming the mission and strategy based on the principles of compliance, and accordingly, this should be taken into account by the management of the enterprise when building a management and security system at the enterprise.

The study of the use of neural networks was addressed by domestic and foreign scientists: Khikin S., Rudenko O. G., Bodiansky E. V., Osovsky S. and others. Neural Networks is a fairly flexible product that gives developers a lot of opportunities to achieve specific goals. Questions of application of information-analytical decision-making systems were investigated by both foreign and domestic scientists: S. Bratushka, M. Demidenko, V. Sitnik, S. Subbotin, L. Shavelyov and others. Problems of building an enterprise information system are covered in the works of O. Frolenko, Y. Panuhnik, O. Sokhatska, but improved with the use of intelligent decision support (IDSS) systems based on neural networks is not highlighted [2].

Therefore, the winner in the competition will be the one who can adapt his strategy and mission based on the principles of compliance.

Research methodology

The theoretical and methodological basis of the research under consideration are the scientific methods of economic theory in the field of compliance and strategic planning using an abstract-logical approach in the process of studying economic processes and phenomena, in particular the following:

– *scientific generalization,* when considering the place of the compliance program in the process of strategic planning, through successive actions to bring together specific single facts into a single whole in order to identify typical features and regularities inherent in the phenomenon being studied. The use of generalization, as a logical process of transition from individual to general or from less general to more general knowledge, allows you to reflect the general features of the strategic planning process at the enterprise and its qualities. The multifaceted types and forms of strategic planning and the inclusion of a compliance program in this process, as a necessary element, presupposes its division into components using generalizing indicators – compliance indicators,

– *a dialectical method*, thanks to which the study examines the economic phenomena of strategic planning with the use of a compliance program at all stages in order to minimize risks in their continuous movement, relationships and interaction, when the accumulation of quantitative changes entails qualitative changes based on change management, and the source of upward development of the enterprise is controlling, which allows specifying and developing a system of enterprise development goals (when determining the place and role of the compliance program in the strategic management of the enterprise),

– *a genetic approach* when studying the macroeconomic environment, world experience and determining the stages of building a compliance program based on the principles of the dialectic of unity and integrity).

– *scientific abstraction*, when applying a compliance program in determining the mission and strategy by using only a part of the set of relevant data about the object and adding to this part some new information that does not directly follow from these data,

– *theoretical provisions of system analysis* when decomposing the activity of the business entity into various subsystems and groups of indicators; when developing a compliance program at the enterprise,

– *methods of economic analysis* involve the imaginary dismemberment of the researched object into its constituent parts (according to various characteristics depending on the goals and objectives of the research), the identification of their internal structure, properties, features, functions, etc. Economic analysis is related to economic synthesis, which consists in determining the relationships between the component parts obtained in the process of analysis and the specified characteristics, their combination and connection into a single whole [3].

Research results

The authors conducted an analysis of the peculiarities of the state of macroeconomic factors of the economy during military operations and in the perspective of its revival, which determine the further process of formation, adjustment and adaptation of the enterprise’s mission and strategy, taking into account the course towards the EU. So, the main features are:

1) the existence of corruption in the country and cases of embezzlement of material resources, as the main factor inhibiting the revival and sustainable development of Ukraine as a whole;

2) the absence of uniform rules, norms, standards and requirements both at the level of enterprises and at the level of the state creates opportunities for the emergence of monopolies, privileged opportunities;

3) a state where there is practically no responsibility for corruption, and certain oligarchic entities operate, when there is no confidence in guarantees of property rights, protection of investors, all this requires immediate reform of the legal and judicial system;

4) there are practically no concepts and programs for the development of industry, its innovative restructuring;

5) inefficient budget policy that does not create incentives and priority directions for the development of Ukrainian enterprises;

6) conditions for the development of business, intellectual entrepreneurship, innovation and capital markets need transparency and improvement due to the reduction of the gap between science and innovation;

7) technological backwardness is observed, which requires increasing efficiency in the field of technology transfer and active participation of the country in international projects on technology exchange and trade;

8) lack of directions for human capital development leads to the outflow of qualified personnel, the quality of professional training of specialists decreases, there is a shortage of specialists in certain specialties, in particular in metallurgy. This leads to a decrease in the motivation of foreign investors to invest in the production capacity, capital and labor force of the country.

But it should be noted that a huge «plus» is that Ukraine, which has become a candidate for the EU, will receive resources for standardization, and in the future will enter the single European market. In such conditions, the way to create compliance programs at enterprises will ensure a soft transition period and allow the country to integrate into the European economic space.

In the Decree of the President of Ukraine «On the Sustainable Development Goals of Ukraine for the period until 2030 [4], the main guidelines for achieving the long-term sustainable development goals for Ukraine until 2030 are provided.

On March 3, 2021, the government approved the revised National Economic Strategy until 2030.

The document defines strategic steps for the development of industry, the agricultural sector, mining, infrastructure, transport, the energy sector, information and communication technologies, creative industries and the service sector. The Strategy also takes into account important cross-cutting areas – digitalization, the «green» course, development of entrepreneurship and balanced regional development.

Among the principles on which the National Economic Strategy is built are European and Euro-Atlantic integration, inviolability of private property, rule of law, intolerance to corruption, free and fair competition, equal access for business [5].

Experts note the correct tasks that were not previously in state programs:

• tax on withdrawn capital;

• launch of the accumulative pension system;

• creation of the International Financial Center;

• capital amnesty;

• transition to medium-term budget planning;

• adjustment of NBU policy: regulation of inflation taking into account stimulation of the economy;

• regulation of the cryptocurrency market;

• stimulation of the market of non-banking financial services;

• support of Ukrainian exporters;

• tax benefits for investors;

• development of industrial parks [6].

Thus, the state has a strategy that serves as a base for all economic entities, it defines values, long-term goals and conditions that allow the enterprise to interpret them into its own values and develop in accordance with them.

It is the mission of the enterprise that determines the values, which then turn into ethical standards. When members of an organization adhere to their ethics, they are, in effect, adhering to these standards.

Managers and compliance specialists are faced with such questions as «Does this policy (mission, strategy) meet regulatory requirements?», which often requires a «yes/no» answer. Therefore, it is extremely important that all personnel in the organization have a thorough understanding of exactly what compliance means. Failure to bridge the gap and effectively communicate compliance requirements between departments and individual performers can lead to inefficiencies and disagreements. And this, in turn, leads to risks of financial losses and legal consequences. However, compliance is more than meeting the requirements of the law. Fulfillment of requirements should be considered, on the one hand, as a necessary minimum for safe work and resistance to external threats, and on the other hand, as continuous work to meet the needs and expectations of various interested parties and stakeholders. This applies to every performer in the organization, and failure to allocate adequate resources to support compliance can have dire consequences.

As can be seen from Fig. 1, the definition of the mission and strategic planning includes a compliance program, which is based on risk assessment and is included in the information system of the enterprise using a decision support system. Why is it so important not to separate compliance and risk? Because compliance should be seen as an integral part of risk, i.e. compliance management efforts, directly related to associated risks. Risk management, like compliance management, is an ongoing process that requires constant monitoring and evaluation.

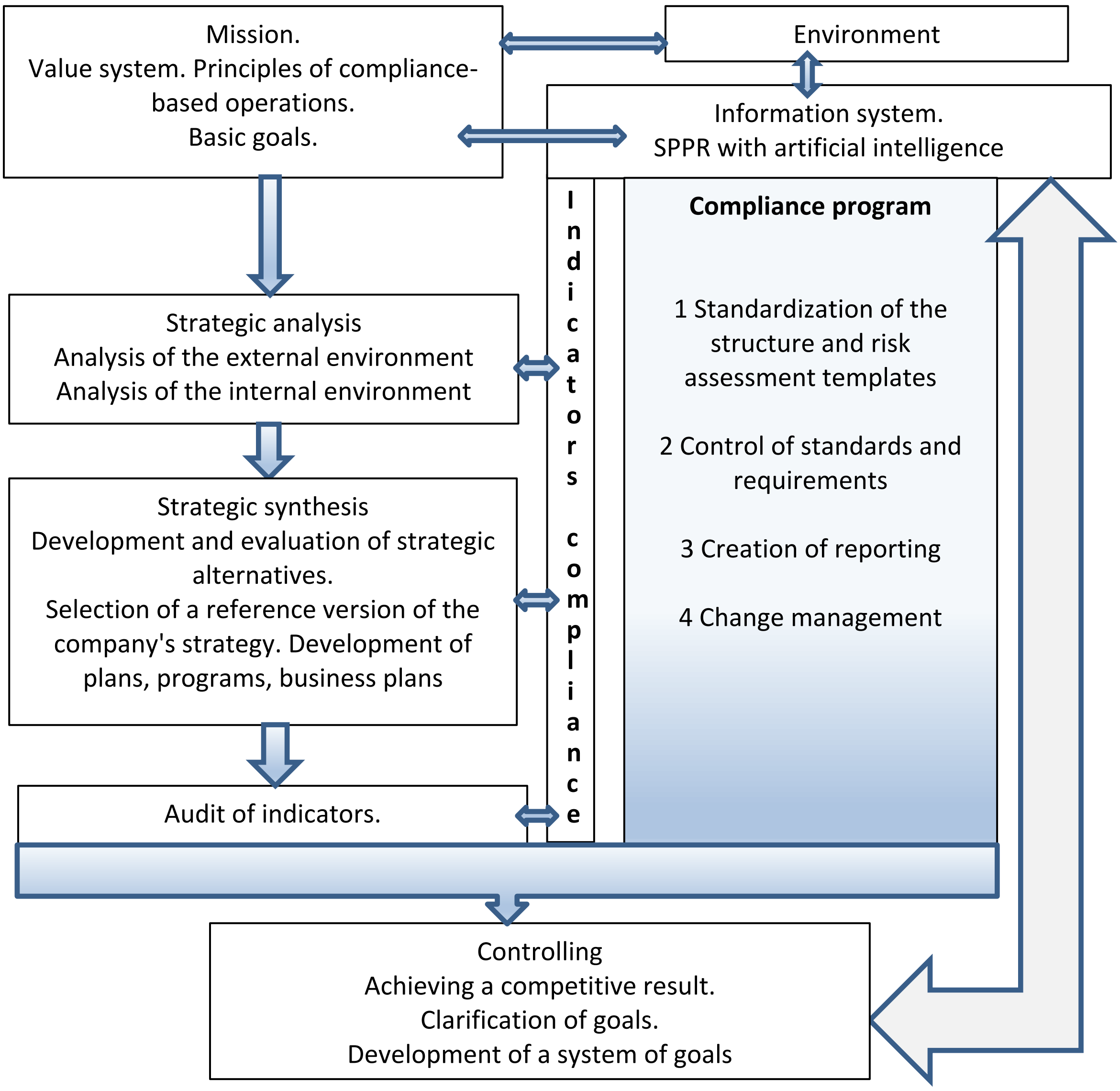

Fig. 1. The place of the compliance program in the strategic planning system of the enterprise* (development of the authors)

Let's consider the essence of the main stages in more detail [7].

1. Standardization of the structure and assessment templates. A carefully curated risk library can categorize risks according to regulatory requirements, helping to prioritize specific areas and optimize required corrective actions. This ensures clarity and objectivity when disclosing information.

2. Control of standards and requirements. It is necessary to link standards and requirements with the appropriate means of control – standards and actions to reduce risks go hand in hand; examining the relationships between them ensures the effectiveness of each control related to compliance efforts.

3. Creation of reporting. Structured reports provide flexibility and efficiency. Dynamic reporting is an integral part of compliance, so it's important to demonstrate that your business is compliant with customized reporting.

4. Change management. The sooner policy adjustments are made in response to changing regulatory requirements, the better. This allows you to quickly notify the appropriate people when changes occur.

The peculiarity of the proposed co-compliance program is that it can be implemented in practice using a decision support system (DSP) based on artificial intelligence with neural networks.

Conclusions

The following results were obtained during the study:

1. The peculiarities of the state of macroeconomic factors of the economy during military operations are analyzed. The main threats are formulated and the ways out and reconstruction of the Ukrainian economy are planned. The National Economic Strategy until 2030 acts as the main factor for overcoming the crisis. Its advantages and directions are analyzed.

2. The essence of the mission is revealed from the point of view of the concept of compliance. The mission of the enterprise is defined as values, which then turn into ethical standards. And compliance with these standards is the main task of implementing the compliance program at the enterprise.

3. Attention is focused on the need to combine such activities as compliance and risk management. Their mutual influence and the need for a comprehensive approach to the implementation of the compliance program are emphasized.

4. A strategic planning scheme using a compliance program has been developed, which allows using the main stages of compliance when formulating a mission, developing a strategy, and allows you to adjust goals and develop

a system of enterprise goals taking into account changes in regulations and standards, based on the achieved indicators.

5. It is emphasized that the internal audit of the achieved indicators is based on the monitoring of compliance indicators, on the basis of which the compliance program can track deviations and violations at all stages of both strategic analysis and strategic synthesis, and thanks to the decision support system built into the information system of the enterprise with artificial intelligence in the form of neural networks, enterprise management can quickly and, most importantly, effectively respond to violations and manage changes in the legislative sphere, standards, regulations and other risks posed by the external environment.

Thus, the study showed that the mission is formulated on the principles of compliance and the development of an appropriate strategy using a compliance program will allow to avoid and prevent the risks of non-compliance and comply with the current legislation in the company's activities, standards of conduct, manage conflicts of interest, treat customers fairly, protect information flows, combat fraud and corruption, which improves the image and reputation of the enterprise.

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THE ROLE OF INNOVATIVE TECHNOLOGIES IN THE PROCESS OF TRAINING PROJECT MANAGERS

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The article substantiates that the modern world does not keep up with the changes that are taking place. Because of this, the problems of society become the subject of theoretical research already after they have become quite acute and require immediate solutions. The author researched the concept and necessity of implementing project-based learning under the conditions of the digital transformation of education. The innovative technologies that can be effectively used to spread systemic thinking are presented. The considered methods to form systemic thinking, characteristic features, and stages of problem-solving. It has been proven that the solution to the problem is covered in the most detail through the development of a project plan. Therefore, in order to form systemic thinking, it is necessary to use the project-based learning method in the educational process. Based on the research, directions for improving the educational environment for the formation of integration competence in the digital transformation of society are determined.

Introduction

In the era of global changes, there were many problems of educational processes transformation, and therefore, there is a need to solve a significant number of new tasks for the training of future specialists.Until the middle of the twentieth century, development, as one of the characteristics of system dynamics, considered within the framework of the so-called classical science [1]. The axiomatic provisions of this science included such features as strict determinism and progressiveness of development processes, leveling of the role of the individual and social groups. The environment understand as simple and sustainable systems, and was defined by the acronym SPOD (Steady, Predictable, Ordinary, Definite), was an example of stability and sustainability. Management actions in such systems considered mainly as functions of maintaining thesystem parameters balance, counteracting the stochastic perturbations of the macro-environment, ensuring the optimization of theresources use. However, our SPOD world was quickly replaced by the world of VUCA (Volatile, Unstable, Complex,Ambiguous), which was not going to stabilize its course, but only accelerated the speed of change. Moreover, today modern man has to adapt to the world of BANI (Brittle, Anxious, Nonlinear, Incomprehensible) [2]. The new world generates a bunch of abbreviations of 4 letters. Therefore,Oxford University’s Executive Education Program uses TUNA acronym (Turbulent, Uncertain, Novel, Ambiguous) instead of the more familiar VUCA world. Another interesting acronym that describes the modern world

DELA (Dynamic, Emergent, Liminal, Anthropocentric) has an interesting anthropological perspective [3]. The real world is constantly changing, in the process of emergence and formation of intermediate transitional state. In this space of growing chaos, not everyone realizes that our old ideas about building the world and the management tools we use no longer work. Today's daily news feed confirms that most international institutions, country leaders and academics do not understand how to act in this new world. Moreover, it is necessary to act much faster than it was in the last century. Everything leads us to understand that most of the old system models no longer work and questions arise about how and why to train modern specialists.

Analysis of literature and the problem under study

In the second half of the twentieth century, the views of non-classical science became more common, the object of research of which were complex human-dependent systems that have their own subjective judgments about any managerial actions.

The mechanisms of nonlinear development of events are considered in the general theory of self-organization of systems, which is used only for so-called dissipative systems. I. Prigozhin [4] first introduced the concept of dissipation of matter and energy in the system. The existence and dynamics of dissipative systems depends on their constant exchange with the environment. If the exchange stops, such a system collapses. Obviously, any system, constantly exchanging various materials, energy and information with the environment, refers specifically to dissipative systems. Characteristic features of dissipative systems are unbalance and nonlineurability [3].

Unbalance arises precisely due to the presence of processes of exchange of energy, information and substance between the elements of the system itself and characterizes fluctuations in structure, uncertainty of situational interaction between them. Such fluctuations lead to nonlinearity – a violation of the linear nature of the proportionate relationship between external influence on the system and its corresponding reaction [5]. Now, minor influences can lead to a complete change in the structure and complexity of the system, and significant influencescan cause insignificant consequences. Fluctuations in the level of the internal structure of the system described in such categories as «order» and «chaos» [6].

The growth of the structural order degree is due to the system's desire for constant development, while the generators of development are disagreements, contradictions, ambiguity, and not universalism [7].

Ukrainian scientists V. Seminozhenko and V. Geyets emphasize that «...one of the key problems of Ukrainian strategic documents is the lack of understanding of dynamism, variability... Virtually every document does not take into account the changes that are taking place... We are constantly responding to obvious «surprises»... And this is just the beginning...» [8, p. 4]. Itis clearthat our old ideas about economic models and management tools no longer work.

The current state of society demonstrates that the world has not kept pace with the changes taking place, as a result, of which the problems of society become the subject of theoretical research after they have sufficiently aggravated and need immediate solutions. With the old models of thinking, humanity cannot achieve sustainable development that meets the survival needs of future generations. The paradox of the existence of the modern world is that the number of problems that need urgent solutions is not decreasing, but, oddly enough, growing. In these conditions, the importance of the formation of critical system thinking, the ability to creatively solve problems and innovative cooperation is growingfor scientists.

The purpose and objectives of the study

The purpose of the studyis to substantiate the role of project competencies as a specific managerial component of the integral competence of a modern manager capable to make responsible decisions in the face of growing environmental uncertainty and nonlineurability.

Methodical research materials

Ukraine obtained the status of a candidate for EU membership on June 24, 2022, that causes large-scale reforms in the seventh direction. The methodology of project management allows many developed countries to solve the problems of reforming the state in conditions of strict resource and time constraints. The constant growth of data volumes for analysis and the rapid development of information technology, it could argued that this task is constantly complicated.

The importance of systematic learning for both business and the academic world has led to the emergence of research related to measuring people’s ability to innovate. In particular, some researchers propose to consider innovative competence as a set of 5 main components and evaluate a person on each of these properties: initiative, creativity, critical thinking, cooperation and teamwork [9].

The integral competence of all levels managers is «a systematic and natural process of progressive changes in the information and research competence of the individual in accordance with the needs of a digital society, which implies the ability to master new knowledge, improve skills and abilities, gain new experience in the use of information and digital technologies» [10]. The development of Ukraine requires highly qualifiedmanagement personnel, which are necessary for the successful systematic management of innovative projects.

Paragraph 3 of the National Qualifications Framework states that competence is «the ability of a person to perform a certain type of activity, expressed through knowledge, understanding, skills, values, other personal qualities». It also defines integral competence as universal competencies that do not depend on the subject area, but are important for the successful further professional and social activities of the applicant in various fields and for his personal development [11].

Integrated project competence should combine professional managerial, legal, economic, analytical, other special knowledge and skills that are expressed through the ability to quickly respond to problems and changes and the ability to work in a team within the relevant strategies and programs.

To combine theoretical knowledge and practical skills, pedagogical science offers several interesting teaching methods. Therefore, Problem Based Learning (PBL) is a method in which students are offered to solve complex problems, which allows them to master the system principles and decision-making.

The case-study approach (learning through parsing real cases) originated at Harvard Business School in the early 1920s. It was then that the first collection of cases was published at the Harvard Business School, since the teachers of the program realized that there are no textbooks that prepare students for real working situations. Unlike the exact sciences, there is no single correct answer in the cases, since the number of components of the problem is always very large [12]. Therefore, in cases it is impossible to know one solution, you have to choose the most effective, and then look at what other participants offered. The value of case technology lies in the fact that it helps to activate a certain baggage of knowledge that must be learned when solving this problem, that is, thanks to cases, students learn to use the knowledge gained in practice. Therefore, cases can be considered as a kind of laboratory for brain training in search of solutions to various situations.

The project activity of students carried out in the application of the Project Based Learning method requires not only the study of the object and subject of research of a particular scientific field, but also requires the study of related branches of science, which will lead to the results of metacognition and integrated learning activities. The peculiarity of project education is that it combines both practical work (manual labor), but also has a creative component and scientific research. Integration of disciplines (natural sciences, general technical and technological, teaching art and socially significant disciplines) is based on project activities and can become the basis for innovation in the future. One of the most effective methods of forming integral project competencies is project activities aimed at solving complex interdisciplinary problems. The method of project-oriented learning is similar to problem learning, but requires bringing the problem solution to the particular project development. Work on own project can become an important component of the educational process aimed at forming the ability to work in the information space, professional development focused on the systematization of professional competencies [13]. Table 1 shows a comparison of the methods of integral system competenceformation.

Table 1

Comparison of methods for the integral competence formation

Method	Advantages	Disadvantages
Problem learning	Associated with one of the subject branches. The product may simply be a proposed solution expressed in writing or in an oral presentation.	Associated with one of the subject branches. Tries to structure the problem with the help of thematic examples and fictitious scenarios for the development of the problem.
Case-study method	It contains real, very real tasks. The professor presents a specific complex problem and students are looking for and developing proposals for solving it. The task has clear stages. It helps to activate a certain baggage of knowledge that must be learned when solving this problem.	It is impossible to know one solution, you have to choose the most effective, and then see what other participants offered. It does not come to a clear development of the final product.
Project based learning	It involves alkalization to «real» tasks and structured activities of students (often questions or group), which is advisable to evaluate on individual tasks. Includes detailed development of project product creation processes using decomposition and synthesis methods.	It can be long (weeks or months) of open projects, which requires the ability to change the management model depending on the phase of the project.

From a structuralpoint of view, a complex scientific process divides into smaller, logically related units that draw students' attention to important features of scientific thinking. These individual units call stages of research, and their interrelated set forms a certain life cycle of solution development. The model of the research learning cycle proposed by the authors M. Pedaste, K. Manoli, consistsofthe following stages: orientation, conceptualization, investigation, discussion, and conclusions [14]. There is no one best way to determine the ideal life cycle of a project**.** Within the framework of the Project Management Institute methodology, the classic life cycle of the project has 5 phases: initiating, planning, executing, monitoring, and closing [15]. The integration competence of the project manager allows showing special qualities at each stage of the project life cycle. Stages of the creative process of solving the problem through the project development as indicated on the table 2.

Table 2

Stages of solving the problem through the project

Project Management Methodology and Logical-Structural Analysis	Stage 1. Preparation	Intellectual-creative preparation
		The manifestation of social needs
		Choose an area of interest
	Stage 2. Formation of the concept	Collection and analysis of information
		Define the purpose of the project
		Directed search of means
	Stage 3. Search phase	Free generation of ideas
		Formation of alternatives to achieve the goal
		Selection the optimal strategy for achieving the goal
	Stage 4. Detailed Planning	Description of the general concept of the project
		Structuring the project's works
		Detailed project planning
	Stage 5. Implementation and evaluation	Checking the execution of work according to the plan Management of critical processes at the stage of project implementation Development of solutions and measures to get out of crisis situations Assessment of the achievement of planned project results

On the basis of the system analyststraining, a description of digital tools for the formation of the main activities during the main stages of the project life cycle for solving complex problems has been presented (see table 3).

Table 3

Digital tools for the development of integrated system competence

Digital tools that provide a certain educational activity	Examples of digital tools to support this learning activity
Tools for finding information	
Search tools	Google, Google Trends, Google Public Data Explorer, Bing, Baidu, BibMe, EasyBib,
Tools for working with cloud storage	GoogleDrive, 4Shared Free File Sharing, Dropbox
Tools for online translation	Translate. Google, PROMT, Context, Lingualeo English Translator, DeepL Translator
Tools for conducting a survey via the Internet	Kahoot, Socrative, Mentimeter, Google Forms
Tools for working with online documents	GoogleDocs, MS Office 365, ThinkFree
Manage teams and communities	Jira, Trello, GitHub, Meetup, Google Drive, Google Analytics
Data visualizationtools	
Tools for creating conceptual maps	Miro, Mindmeister, Mindomo, Seeing Reason, Showing Evidence, Webspiration
Creation ofthe graphics	Corel Draw, Paint, Aviary, NGA, Twirler,SwatchBox
Editingpictures	Fotoshop, FotoFlexer, Picnik, Pixlr, Pixlr Express
Tools for project management	
Calendars	MS Project, Sure Track, Famundo, Google Calendar, HiTask, Spider
Tasks and tracking of the main stages	MyNoteit, Teamwork Project, Jira, Trello,
To-do lists	MyNoteit, Remember the Milk, To Do List, Google Keep
Tools for communication and exchange of views	
Tools for online chatting	Zoom, Teams, WhatsApp, Google Talk, Skype Chat
Tools for communicating with mobile devices	Teams, Viber, Telegram, WhatsApp, Messenger
Video and audio conferencing	Zoom, Teams, Google Video, WhatsApp, Skype, Tokbox

The dynamic development of new information technologies and professionally oriented software necessitates to provide the future project manager not only with high-quality professional education, but also to develop the ability to quickly update and complement the acquired knowledge and skills, to form a desire for constant self-development and self-improvement. The widespread use of information and communication technologies capabilities in the educational environment has led to the emergence of new components in the education system that open up wide opportunities for improving the educational process.

Thus, project management teachers should significantly expand their arsenal of interactive methodical tools. The gradual integration of new technologies into the processes of higher education opens up for teachers simply unlimited opportunities for experimentation. Conducting interactive training activities requires the use of a wide range of technical means of training, such as video and media tools, interactive tables, illustrations, etc. Although, in order to avoid annoying surprises, the teacher needs to prepare much more for interactive classes than for a lecture session.

Conclusion

Project management is a powerful means of rebuilding the world aimed at solving complex problems by creating a project product. The integration of digital education into project management is very important for the development of project education in Ukraine. Educational environment has to attract students in the project management study, to create positive motivation in them, to stimulate them to find new methods for solving problematic situations.

The modern educational environment creates favorable conditions for training a very largenumber of participants in the educational process at the same time. This is especially important, since modern electronic systems attract students to scientific education by interesting means for them and make educational processes independent of the material and technical base of the educational institution. All this increases the competition in the market for the provision of educational services and demands from scientists not only high professional skills, but innovation and creativity.

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DEVELOPMENT OF A METHODOLOGY FOR SOLVING PROBLEMS OF SELECTING INFORMATIVE ATTRIBUTES THAT CHARACTERIZE THE STATE OF THE LIFE CYCLE OF RADIO ELECTRONIC MEANS

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The methods of identification of states of radio electronic means, which distinctive feature is providing formulation of the rule of division of sets in space of states and the rules establishing correspondences between sets of parameters and values of indicators of efficiency of life cycle of radio electronic means (LC REM), application of the mentioned rules gives the possibility to construct and control algorithms of optimization of LC REM indicators. The methods for solving the problems of selecting informative REM attributes and displaying monitoring as a process LC REM, which are distinguished by the use of geometric interpretation, consideration of selection problems in the attribute space, and consequently visualization of the analysis and optimization of monitoring are considered.

Introduction

A distinctive feature of radio electronic means (REM) is the presence of a large number of monitored parameters. Monitoring, providing an opportunity to measure and record values and rates of change of REM parameters, can have additional capabilities, giving an insight into the state of REM under a set of parameters as a statistical ensemble. It is known in science when description of behavior of micro ensemble of particle parameters gives possibility to determine macro parameters of systems consisting of them, create phenomenological theory and use for estimation and management of state of such systems. An example is a physical medium consisting of atoms and molecules, micro-parameters here are coordinates and impulses of these particles, phenomenological theory is thermodynamics, macro parameters are volume, pressure, temperature, etc. Observation, in the field of vision, which gets a phase plane, on which it is possible to observe decay and mixing of statistical ensemble of REM parameters, gives additional possibilities for monitoring of life cycle of radio-electronic means (LC REM).

The functional problem of selecting informative features for monitoring LC REM, as well as reducing their list, reducing uncertainty can be solved within the methodology of developing a dictionary of features in systems of classification and recognition of the state of objects [1, 2, 3]. Here the purpose of the selection is to provide the optimal recognition.

Statement of the research problem

The working dictionary should use only the attributes, which, on the one hand, are the most informative and, on the other hand, can be accessible (for example, in terms of costs) for measurement. The definition of the dictionary of attributes in conditions of restrictions on the cost of creation of technical means of observation has peculiarities.

If we denote the features of objects by δ_j, $j=1, 2,..., N$, then each object in the N-dimensional feature space can be represented as a vector $x=\left(x_1, x_2, ..., x_N\right)$, with coordinates characterizing the properties of objects.

To determine the measure of proximity or similarity between objects in the N-dimensional feature vector space, a metric is introduced. One can use the Euclidean metric

$$d^2\left(w_{pk}, w_{ql}\right)=\sum_{j=1}^{N}\left(x_{pk}^{j}-x_{ql}^{\;j}\right)^2, \tag{1}$$

$$p, q=1, 2, ..., m; \quad k=1, 2, ..., k_p; \quad l=1, 2, ..., k_q,$$

where x_{pk}^{j} – are the values of the j-th feature of the k -th object of the p-th class, i.e. the object of the q-th class, i.e. the object w_{ql} .

As a measure of proximity between objects of a given class Ω_p, $p=1, 2, ..., m,$ we will use the value

$$S\left(\Omega_p\right)=\sqrt{\frac{2}{k_p}\frac{1}{k_{p-1}}\sum_{k=1}^{k_p}\sum_{l=1}^{k_p}d^2\left(w_{pk}, w_{pl}\right)}, \tag{2}$$

which has the meaning of the root-mean-square scatter of the class or the root-mean-square scatter of the objects within the class Ω_p , as a measure of proximity between objects of a given pair of classes Ω_p and Ω_q, $p, q=1, ..., m,$ – value

$$R\left(\Omega_p, \Omega_q\right)=\sqrt{\frac{1}{k_p k_q}\sum_{k=1}^{k_p}\sum_{l=1}^{k_q}d^2\left(w_{pk}, w_{ql}\right)}, \tag{3}$$

which has the meaning of the root-mean-square scatter of objects of classes Ω_p and Ω_q.

The set of features used in the working dictionary can be described by an N-dimensional vector $\mathrm{A}=\left(\alpha_1, \alpha_2, ..., \alpha_N\right)$, with components take values 1 or 0, depending on whether it is possible or impossible to determine the corresponding feature of the object.

Taking into account the α square of the distance between two objects w_{pk} and w_{ql}

$$d^2\left(w_{pk}, w_{ql}\right) = \sum_{j=1}^{N} \alpha_j \left(x^{(j)}{}_{pk} - x^{(j)}{}_{ql}\right)^2 . \tag{4}$$

Consequently, the root-mean-square scatters of the class Ω_p and objects of the classes Ω_p and Ω_q can be written accordingly as follows

$$S\left(\Omega_p\right) = \sqrt{\frac{2}{k_p}\frac{1}{k_p - 1}\sum_{k=1}^{k_p}\sum_{l=1}^{k_p}\sum_{j=1}^{N} \alpha_j \left(x^{(j)}{}_{pk} - x^{(j)}{}_{pl}\right)^2} , \tag{5}$$

$$R\left(\Omega_p, \Omega_q\right) = \sqrt{\frac{1}{k_p}\frac{1}{k_q}\sum_{k=1}^{k_p}\sum_{l=1}^{k_q}\sum_{j=1}^{N} \alpha_j \left(x^{(j)}{}_{pk} - x^{(j)}{}_{pl}\right)^2} . \tag{6}$$

It can be assumed that the costs of using a feature are proportional to their informativeness, i.e., to the number of features of objects that can be determined with their help. This assumption (leaving aside the question about the accuracy characteristics of observation tools) is quite general.

Thus, the costs of using the features

$$C = C\left(\alpha_1, ..., \alpha_N\right) = \sum_{j=1}^{N} C_j \alpha_j , \tag{7}$$

where C_j – the cost of determining the *j*-th feature.

As an indicator of quality or efficiency of the designed recognition system we consider a functional, which in general depends on the function $S\left(\Omega_p\right)$, $R\left(\Omega_p, \Omega_p\right)$ of the decisive rule $L\left(w, \left\{w_g\right\}\right)$

$$I = F\left[S\left(\Omega_p\right);\ R\left(\Omega_p, \Omega_q\right);\ L\left(w, \left\{w_g\right\}\right)\right]. \tag{8}$$

Let the value $L\left(w, \left\{w_g\right\}\right)$ be a measure of proximity between a recognizable object w and a class Ω_g, $g = 1, 2, ..., m$, given by its objects $\left\{w_g\right\}$. As this proximity measure, consider the value

$$L\left(w, \left\{w_g\right\}\right) = \sqrt{\frac{1}{k_g}\sum_{g=1}^{k_g} d^2\left(w, w_g\right)} , \tag{9}$$

which is the root-mean-square distance between the object w and the objects of the class Ω_p .

The decisive rule is $w \in \Omega_g$, if

$$L\left(w,\left\{w_g\right\}\right) = extr\, L\left(w,\left\{w_i\right\}\right). \tag{10}$$

It is important to note that the reduction of the value $S\left(\Omega_p\right)$, «compression» of objects belonging to each given class, with a simultaneous increase of $R\left(\Omega_p,\Omega_q\right)$, i.e. «dilution» of objects belonging to different classes provides, ultimately, an improvement in the quality of the recognition system. Therefore we will connect the improvement of the efficiency of the system with the achievement of the extremum of the functional *I*.

The statement of the research problem can be formulated as follows.

Let the set of objects be subdivided into classes Ω_i, $i = 1, \ldots, m$, all classes are described a priori in the language of features x_j, $j = 1, \ldots, N$, and funds equal to C_0 are allocated for the creation of technical means of observation. It is required, without exceeding the allocated amount of funds, to construct a working dictionary of attributes, which provides the maximum possible efficiency of the system.

Thus, the problem is reduced to finding a conditional extremum of a functional of the form (8), i.e. to determining *A* implementing

$$\underset{\alpha}{extr}\; I = \underset{\alpha}{extr}\, F\left[S\left(\Omega_p\right);\; R\left(\Omega_p,\Omega_q\right);\; L\left(w,\left\{w_g\right\}\right)\right]$$

$$C = \sum_{j=1}^{N} C_j \alpha_j \le C_0. \tag{11}$$

Possible kinds of the functional. Let us consider some particular kinds of the functional (11). If the required efficiency of the recognition system can be achieved by a more compact arrangement of objects of each class under some conditions concerning the value of $R\left(\Omega_p,\Omega_q\right)$, then the problem is reduced to finding

$$\min_{\alpha} \max_{i=1,\ldots,m} \left[S\left(\Omega_i\right)\right] \tag{12}$$

at

$$\sum_{j=1}^{N} C_j\, \alpha_j \le C_0 \text{ and } R\left(\Omega_p,\Omega_q\right) \ge R_0^{(pq)}. \tag{13}$$

If the required efficiency of the system can be achieved by «removing» from each other objects belonging to different classes under certain conditions concerning the value of $S\left(\Omega_i\right)$, $i = 1, \ldots, m$, then the problem is reduced to finding

$$\max_{\alpha} \min_{p,q=1,\ldots,m} \left[R\left(\Omega_p,\Omega_q\right)\right] \tag{14}$$

at

$$\sum_{j=1}^{N} C_j \alpha_j \le C_0 \text{ and } S\left(\Omega_i\right) \le S_0^i . \tag{15}$$

If the proper efficiency of the system can only be achieved by increasing the ratio of distances between classes to the root-means-square scatter of objects within classes, then the problem is reduced to finding

$$\max_{\alpha} \min_{p,q=1,\dots,m} \left[\frac{R^2\left(\Omega_p\ \Omega_q\right)}{S\left(\Omega_p\right) S\left(\Omega_q\right)} \right] \tag{16}$$

at

$$\sum_{j=1}^{N} C_j \alpha_j \le C_0 . \tag{17}$$

Solving the problem of selecting informative signs that characterize the state of lc rem processes

The problem considered above is a generalization of the nonlinear programming problem. The optimality C^0 conditions for it can be formulated as follows: for the vector to be an optimal strategy, it is necessary that there exist a scalar $\beta \ge 0$ and a vector $\mu = \left\{ \mu_1, \dots, \mu_n \right\}$ such that

$$\left.\begin{aligned} &\left[\sum_{r=1}^{n} \mu_r \rho_r^j \right] \frac{dP_j\left(C_j^0\right)}{dC_j} = \beta, \quad j = 1, \dots, N_p; \\ &\sum_{j=1}^{N_p} C_j^0 = C_0 \ ; \\ &\sum_{r=1}^{n} \mu_r = 1, \mu_r = 0, \text{если} \sum_{j=1}^{N_p} \rho_r^j P_j\left(C_j^0\right) > W\left(C^0\right). \end{aligned}\right\} \tag{18}$$

The introduction of a scalar β and a vector μ increases the number of unknowns C_j^0, μ_r and β to the value $N_p + n + 1$. However, the number of equations equals the number of unknowns, since for any *r* either $\mu_r = 0$, or

$$\sum_{j=1}^{N_p} \rho_r^j P_j\left(C^0{}_j\right) = W\left(C^0\right). \tag{19}$$

Thus, the solution of the system of equations (18) makes it possible to determine the composition of the features of the working dictionary and the optimal allocation of costs for the creation of observational means of the recognition system under the assumption of dependence $P_j = P_j\left(C_j\right)$ and limitations on the total cost of these means.

With the limitations associated with the possibility of using the entire dictionary of features, the task of selecting a limited list (up to 2–3 features) arises. Here it is possible to be guided by the location of the individual components of the feature vector relative to the boundaries of the serviceability area of the monitoring objects.

Since at the boundary value of the parameter $y^j_{гр}$, the end of vector X must be at the boundary of the serviceability area, it is necessary that the equality

$$x^i{}_{гр} = a^i_j y^j{}_{гр} . \tag{20}$$

In statistical estimation, the correlation coefficient r_{ij} between the parameters can serve as an additional criterion for selection. Since the maximum correlation coefficient provides the maximum amount of information

$$J\left(y^j\right) = H\left(y^i\right) - H\left(y^j / y^i\right), \tag{21}$$

of the parameter y^i. Here $H\left(y^i\right)$ – initial entropy; $H\left(y^j / y^i\right)$ – conditional entropy of the object after measuring the parameter y^j.

The use of binary correlation algorithms makes it possible to formalize and automate the processes of input, processing and recognition of the resulting image with the participation of the decision maker (DM).

Identification of LC REM process state

Identification of LC REM implies the existence of rules defining the states of REM. The attributes allowing to distinguish the states of the monitored object are performance indicators, which for the allocated state will have a given or extreme value. In order to identify REM states in the process of monitoring, it is necessary to check whether the observed parameters are those that provide performance criteria, whether they belong to the set on which the value of performance indicators will have set or extreme values. To solve the problems of state estimation, it is possible to use methods of functional analysis [4, 5].

Objects of observation – parameters and characteristics of REM can be considered as points of vector and functional spaces. For all possible pairs of points on the set Q, there exists a binary relation of comparative efficiency: a point x is more efficient than y if and only if $(x, y \in \Phi)$ or in another notation $x \, \Phi \, y$. Providing LC REM solves the problem of selecting the kernel – the set of maximal elements from by the X binary relation $\Phi : X^* = Max\,(Q, \Phi)$. It is assumed that the solution to the problem exists, i.e. the set X^* is not empty. In many problems we can assume that the solution – set X^* – consists of one element, and the relations between the elements are established with the help of functionals $\Lambda(x)$. For example, point x is more efficient than y when $\Lambda(x) < \Lambda(y)$ or $\Lambda(x) > \Lambda(y)$. It can be shown that in the problems of determining effective points $x_0 \in X^*$ in the presence of constraints $x \in Q_1$, the functional $f = \lambda \Lambda'(x_0)$, where $\Lambda'(x_0)$ is the Frechette derivative at the point x_0, is a reference functional to Q_1, at the point x_0 (i.e. $(f, x_0) < (f, x)$ for all $x \in Q_1$.

Thus, the task of analyzing the results of observations in the monitoring process is reduced to determining the reference functionals in the observation points, which makes it possible to assess the deviation of the observed points from the effective ones.

In terms of functional analysis: let Q be a set in a linear topological space E, E' – a conjugate space, $x_0 \in Q$ – an outermost point Q, K_b – a cone of possible directions in Q at the point x_0, K_k – a cone of tangent directions for Q in x_0. If we denote the set of linear functionals, referenced to Q at the point x_0, by Q^*, then $Q^* = f \in E', f(x) \geq f(x_0)$ for all $x \in Q$, i.e., the reference functionals and the endpoint $x_0 \in Q$ allow us to distinguish the set Q. It can be shown that if Q is a closed convex set, then $Q^* = K_k^*$, i.e., it makes cones formed by the set of linear functionals, reference to Q at x_0. The cone of tangent directions can be defined by the Frechette derivatives of the operators (convex functions) which link the sets of parameters and performance measures.

Let's consider the methods of finding K^* for the ways of setting K with the help of different functionals.

Variant 1: For a cone of decreasing directions K_0. A functional $\Lambda(x)$ in linear space E has a derivative $\Lambda'(x_0, g)$ at a point x_0 in the direction g, i.e., there exists

$$\frac{\lim}{\varepsilon \to +0} \frac{\Lambda(x_0 + \varepsilon g) - \Lambda(x_0)}{\varepsilon} = f(x_{0,} g). \quad (22)$$

$\Lambda(x)$ satisfies the Lipschitz condition in the neighborhood x_0 (for some $\varepsilon_0 > 0$ will be $\varepsilon_0 > 0$ at all $\|x_1 - x_0\| \le \varepsilon_0$, $\|x_2 - x_0\| \le \varepsilon_0$)) and $\Lambda'(x_0, g) < 0$, then $\Lambda(x)$ – correctly decreasing at x_0, and $K = \{g : \Lambda'(x_0, g) < 0\}$.

Variant 2. For a cone of possible directions. In the case of a set which is not defined by a functional. If Q is a convex set, then the set of decreasing directions K_b at a point x_0 has the form

$$K_b = \{\lambda(Q - x_0), \lambda > 0\},$$

(i.e. $K_b = \{g : g = \lambda(x - x_0), x \in Q, \lambda > 0\}$).

Variant 3. For a cone of possible directions. In the case of definition Q by means of affine sets: $E = E_1 \times E_2$, E_1, E_2 are linear topological spaces, the set of efficiency features is defined in E_2, D is a linear operator from E_1 to E_2, $K = \{x \in E,\ x = (x_1, x_2) : Dx_1 = x_2\}$, $K^* = \left\{f \in E',\ f = (f_1, f_2) : f_1 = -D^* f_2\right\}$, and as a reference separating function we can use

$$f(x) = \left(-D^* f_2, x_1\right) + (f_2, x_2) = -\left(f_2, D^* x_1 - x_2\right).$$

The application of this function to divide the sets in the parameter space and to formulate rules that establish a correspondence between the parameter sets and the values of performance indicators can provide identification of states in the LC REM monitoring process.

Variant 4. For a cone of tangent directions. $P(x)$ is an operator from E_1 to E_2, differentiable in the neighborhood of the point x_0, $P'(x)$ is continuous in the neighborhood of x_0, and $P'(x_0)$ maps E_1 to all E_2 (i.e. the linear equation $P'(x_0)g = b$ has a solution g for every $b \in E_2$), the set of tangent directions K to the set $Q = \{x : P(x) = 0\}$ at a point x_0 is a subspace $K = \{g : P'(x_0)g = 0\}$.

Variant 5. A typical case for a cone of tangent directions. Let $x \in R^m$, $Q = \{x : G_i(x) = 0,\ i = 1, ..., n\}$, where $G_i(x)$ are functions continuously differentiable in the neighborhood of point x_0, $G_i(x_0) = 0$, $i = 1, ..., n$, and vectors $G_i'(x_0)$ are linearly independent. Then $K=\{g\in R^n:(G_i'(x_0),g)=0, i=1,...,n\}$. Here $E_1=R^m$, $E_2=R^n$, $P(x)=(C_1(x),\ldots,G_n(x))$, $P'(x_0)$ is a matrix $m\times n$ with i-th column equals $G_i'(x_0)$.

Variant 6. In the process of monitoring, it is necessary to determine whether the effective value of the function REM characteristic $w(z)$, in the simplest case the extreme value of the differentiable target function of one variable is provided, for this purpose it is necessary to check whether the derivative is equal to zero at the observed value of the parameter. For multidimensional target functions and their arguments this problem can be considered within the framework of set theory and functional analysis.

The formalization in the problem of observing the optimal tuning, as one of the LC REM processes, is that it is necessary to evaluate the optimality of the tuning process function $v(z)\in M$ where z is a parameter that determines the numerical value of the required characteristic $w(z)$ of the tuning object to provide a phase trajectory that provides equality $w(0)=c$, $w(Z)=d$, and the extremal value of the integral functional $\int_0^Z \Phi(w(z),v(z),z)dz$, in the presence of the relation given by the differential equation $\frac{dw(z)}{dz}=\varphi(w(z),v(z),z)$.

In problems requiring the maximum correspondence of the optimized characteristic and some desired one, the criterion of minimum of the root-mean-square deviation finds application

$$W_2(X)=\overline{\left(Y(X)-Y^*\right)^2}, \tag{23}$$

where Y^* – the desired or required by the technical specification value of the characteristic.

For a characteristic given by a discrete set of points, the target function

$$W_2(X)=\frac{1}{N}\sum_{i=1}^{N}\gamma_i\left(Y(X,p_i)-Y_i^*\right)^2, \tag{24}$$

where N – the number of discretization points of the independent variable p;

$Y(X,p_i)$ – the number of discretization points of the independent variable;

γ_i – weight coefficient of the i-th value of the optimized characteristic, reflecting the importance of the i -th point in comparison with the others (as a rule, $0 < \gamma_i < 1$).

In some optimization problems it is necessary to ensure that the optimized characteristic exceeds or does not exceed some given level. These optimality criteria are realized by the following functions:

– to ensure that a given level is exceeded

$$W_3(X) = \begin{cases} 0 & \text{at} \quad Y(X) \geq Y_L^*, \\ \left(Y - Y(X)\right)^2 & \text{at} \quad Y(X) < Y_L^*; \end{cases} \tag{25}$$

– to ensure that the set level is not exceeded

$$W_4(X) = \begin{cases} 0 & \text{at} \quad Y(X) \leq Y_U^*, \\ \left(Y - Y(X)\right)^2 & \text{at} \quad Y(X) > Y_U^*, \end{cases} \tag{26}$$

where $Y_L{}^*$, $Y_U{}^*$ – lower and upper limits of the allowable area for the characteristic $Y(X)$.

If it is necessary that the optimized characteristic passes in some acceptable zone (corridor), use a combination of the previous two optimality criteria

$$W(X) = \begin{cases} 0 & \text{at} \quad Y_L^* \leq Y(X) \leq Y_U^*, \\ \left(Y(X) - Y_U^*\right)^2 & \text{at} \quad Y(X) > Y_U^*, \\ \left(Y_L - Y(X)\right)^2 & \text{at} \quad Y(X) < Y_L^*. \end{cases} \tag{27}$$

In cases where you want to realize only the shape of the curve, while ignoring the constant vertical displacement, the shift criterion is used

$$W_6(X) = \sum_{i=1}^{N} \gamma_i \left(Y_i^* - Y(X, p_i) - Y_{cp}\right)^2, \tag{28}$$

where $Y_{cp} = \dfrac{1}{N} \sum\limits_{i=1}^{N} \left(Y_i^* - Y(X, p_i)\right)$.

Important characteristics of computational process and, first of all, the convergence of optimization process depend on the kind of target function. Signs of target function derivatives on controllable parameters do not remain constant in the whole admissible domain, the latter circumstance leads to their gully character (for example, circuit design problems), which leads to large computational costs and requires special attention to the choice of optimization method.

Another peculiarity of target functions is that they are usually multiextremal and along with the global minimum there are local minima.

Multicriteria optimization problems constitute a general class of problems of identification of the set of effective solutions. They are characterized by the fact that a binary relation on the set of alternatives, from which it is necessary to choose, is connected with a set of indices – criteria forming a vector efficiency criterion. This binary relation is generated in different ways. So, if

$$W(x)=\left(W^1(x),...,W^m(x)\right) \tag{29}$$

vector criterion on set X, then the binary relation can be a Pareto relation or a Slater relation. In other cases the binary relation on X is set by the system of DM preferences. It is assumed that the main source of information is a person who has sufficient information to make a (single) decision. Identification of the system of preferences of the DM is one of the main problems in solving multicriteria problems. Usually the procedures for identifying preferences of the DM are built on the language of vector evaluations of alternatives, i.e. based on the values of the vector criterion.

DM decision making is facilitated by finding the Pareto set or Slater set by criterion (29), here methodological problems lose their acuteness to a large extent, since the notion of solving a multicriteria problem has already been clearly defined. There remain difficulties of computational character typical for extreme problems.

Methods for solving the problem of finding efficient (Pareto-optimal) and inefficient (Slater-optimal) alternatives are being intensively developed [6, 7, 8], there are programs, software packages and software systems implemented on computers.

Algorithms based on scalarization – reduction to parametric family of scalar optimization problems have great «visualization».

From convex analysis it follows that if $x_* \in P(X,W)$ is an effective point in a linear multicriteria problem (with linear criteria in polyhedron X), then there exists vector Λ

$$\lambda \in \Lambda = \left\{ \lambda \in E^m \,/\, \lambda_i > 0,\ i=1,\ ...,\ m;\ \sum_{i=1}^{m} \lambda_i = 1 \right\},$$

such that x^* is a solution to the linear and nonlinear programming problem

$$\sum_{i=1}^{m} \lambda_i W^i(x) \to \max_{x \in X}. \tag{30}$$

Inversely, for any $\lambda \in \Lambda$ solution of problem (30) is an effective point.

Hence, it follows that well-developed methods of linear and nonlinear programming can be used for the search of $P(X,W)$ and use the result as an effective set in the process of mapping the situation related to the location of the set of real values of the attribute parameters, relative to the set of their effective values in the implementation of LC REM monitoring.

Conclusion

Methods of solving problems of selecting informative signs for monitoring LC REM, by classifying the states of REM and LC processes in the space of signs, each of which has a certain importance, which allowed to find a comprehensive criterion and formalize the selection procedure.

Methods for identifying REM states that interpret them as elements of conjugate linear spaces and setting initial sets using linear and nonlinear functionals are improved, which makes it possible to formulate rules for separating sets in the space of states and rules that establish correspondences between sets of parameters and values of LC REM performance indicators. The application of these rules makes it possible to construct algorithms for optimization of LC REM performance indicators.

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CONCEPTUAL FRAMEWORK FOR THE AUTOMATION OF THE MONITORING SYSTEM OF NATURAL EMERGENCIES SYNTHESIS

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The system of emergency monitoring is considered. Decomposition of emergency monitoring system is proposed, which allows to define a set of tasks for synthesis of emergency monitoring system at each level in a typical emergency monitoring system. A conceptual model of emergency monitoring system in the form of a «black box» is developed. A system concept of interaction of tasks of synthesis of emergency monitoring system is proposed.

Introduction

To combat natural disasters in Ukraine operates the Unified State System of Civil Protection (USSCP), which consists of functional and territorial units. The activities of the USSCP are aimed at solving the issues of ensuring the necessary level of safety of life of the territory of the state only in conditions where an emergency (ES) has arisen [1].

The territory of Ukraine is characterized by the occurrence of almost the entire spectrum of dangerous natural phenomena and processes of geological, hydrogeological and meteorological origin, which are the sources of natural disasters [2].

Every year there are many reports of natural emergencies causing millions of dollars of damage. By means of new technologies, there are more and more opportunities to respond to changes in the environmental situation on the territory of Ukraine [2–3].

Effective management of life safety of the territory of Ukraine at different levels of administrative-territorial distribution should be based on regular environmental monitoring [3–4].

The issues of development and implementation of ES monitoring system and its integration into the USSCP today remain unsolved.

Analysis of recent publications

Environmental security is given a great deal of attention around the world. There are universally accepted approaches, enshrined in the UN's 17 global Sustainable Development Goals. However, each country has its own laws that regulate the norms of environmental impact and set environmental standards for production enterprises.

Environmental monitoring of territories plays an important role in improving the environmental security of Ukraine.

Environmental engineers, consultants, regional authorities, as well as corporations in the field of mining and processing of minerals, mining, and agriculture use the data obtained by monitoring.

Analysis of scientific literature [3–5] shows that when solving the problem of formation of ES monitoring system of different nature there is a need to study the features of manifestation of non-linear interrelations between the components of life processes in Ukraine in modes of daily functioning and state of emergency.

Nowadays, innovative solutions based on end-to-end digital technologies are increasingly being used for ES monitoring. These are, for example, platform solutions and online services whose data sources can be drones and other equipment with special observation sensors. Such systems can be local, within a specific area of the district, or global - on the scale of one region or the country as a whole [6].

Innovations are becoming particularly in demand as the volume of data collected as part of ES monitoring is growing, and more technological solutions are required for their processing and analysis – including machine learning, artificial intelligence and big data analytics.

In Ukraine, it is necessary to develop an ES monitoring system that should collect information on the state of the environment by combining several existing surveillance and automatic control systems.

In work [2] the integrated functional scheme of information-analytical subsystem of management of ES prevention and elimination processes in the Unified State System of Civil Protection, which has four levels: object, local, regional, state. The realization of complex inclusion in the operating USSCP system vertically from object to state levels of various functional elements of the territorial ES monitoring subsystem and constituent subsystems of situational centers is considered.

However, so far the task of synthesis of ES monitoring and warning system has not been solved.

Main part

According to [2, 7], monitoring is a continuous complex observation of potentially dangerous objects, measurement of parameters of the state of such objects, analysis of their functioning and identification of natural and man-made factors of ES formation. Thus, implementation of the monitoring process is the solution of two tasks: measurement of parameters of the state of potentially dangerous object and analysis of its functioning, identification of natural and man-made factors of ES formation.

The measurement task requires answers to the questions:

– What potentially hazardous objects are we observing, i.e., where are we measuring?

– To define the control points of measurement;

– What do we measure? Define the indicators and units of measurement.

– How do we measure? Define measurement methods and techniques.

– What is the frequency (step) of measurements? Define at what intervals (in what steps) should be made measurements.

In the proposed hierarchical decomposition structure of the ES monitoring system at each level $Urv = \{Urv_E\}$, where $E = \overline{1,4}$, 4 is a number of levels for which it is necessary to monitor, allocate a certain number of MSES sites $Uch = \{Uch_{En}\}$, $n = \overline{1, n^E}$ where n is a site number of each level of the monitoring system, with each of the sites having control points $PKUch = \{PKUch_{Enj}\}$, $j = \overline{1, j'}$ where j' is the number of the control unit (CU) of each MSES section where at least one switching device (SD) is installed – $KUUch = \{KUUch_{Enjq}\}$, $q = \overline{1, q^j}$ where q^j – the number of SDs installed in the control point, in the simplest case the number of CUs and the number of SDs installed in the corresponding CUs coincides with the number of sites.

In this case, each CU will be connected to the data collection and transmission devices (DCTD), which, in turn, will be installed at the points of collection and transmission of information. $TSIUch = \{TSIUch_{Enjqi}\}$, where $i = \overline{1, i'}$, i' – number of the data collection and transmission point at each section of the monitoring system. DCTDs are devices with modules and a programmable logic controller (PLC), which are designed to take readings from measuring instruments $USIUch = \{USIUch_{Enjqim}\}$, $m = \overline{1, m^i}$, m^i – DCTD number.

The exact number of DCTDs will be determined by the list of control points $TKUUch = \{TKUUch_{Enjqimg}\}$. $g = \overline{1, g'}$; g' – control point (CP) number, and the connected measuring devices (MDs) installed in them $SI = \{SI_{Enjqimgpv}\}$,

$v = \overline{1, v^p}$; v^p – the number of measuring devices, by means of which the monitoring indicators are measured at the control points $PKTKUUch = \{PKTKUUch_{Enjqimgp}\}$, $p = \overline{1, p^g}$, p^g – number of the indicator measured in the control point.

The software tool BpWin and IDEF0 were used to develop a conceptual model of MSES. IDEF0 methodology allows to find bottlenecks of business processes, which can be subsequently eliminated [8–10].

A schematic representation of the ES monitoring process can be represented as follows (fig. 1) in the form of a black box, characterized by inputs (source information) and outputs (MSES result), information and resource support (arrows at the bottom) and methodological support (arrows at the top).

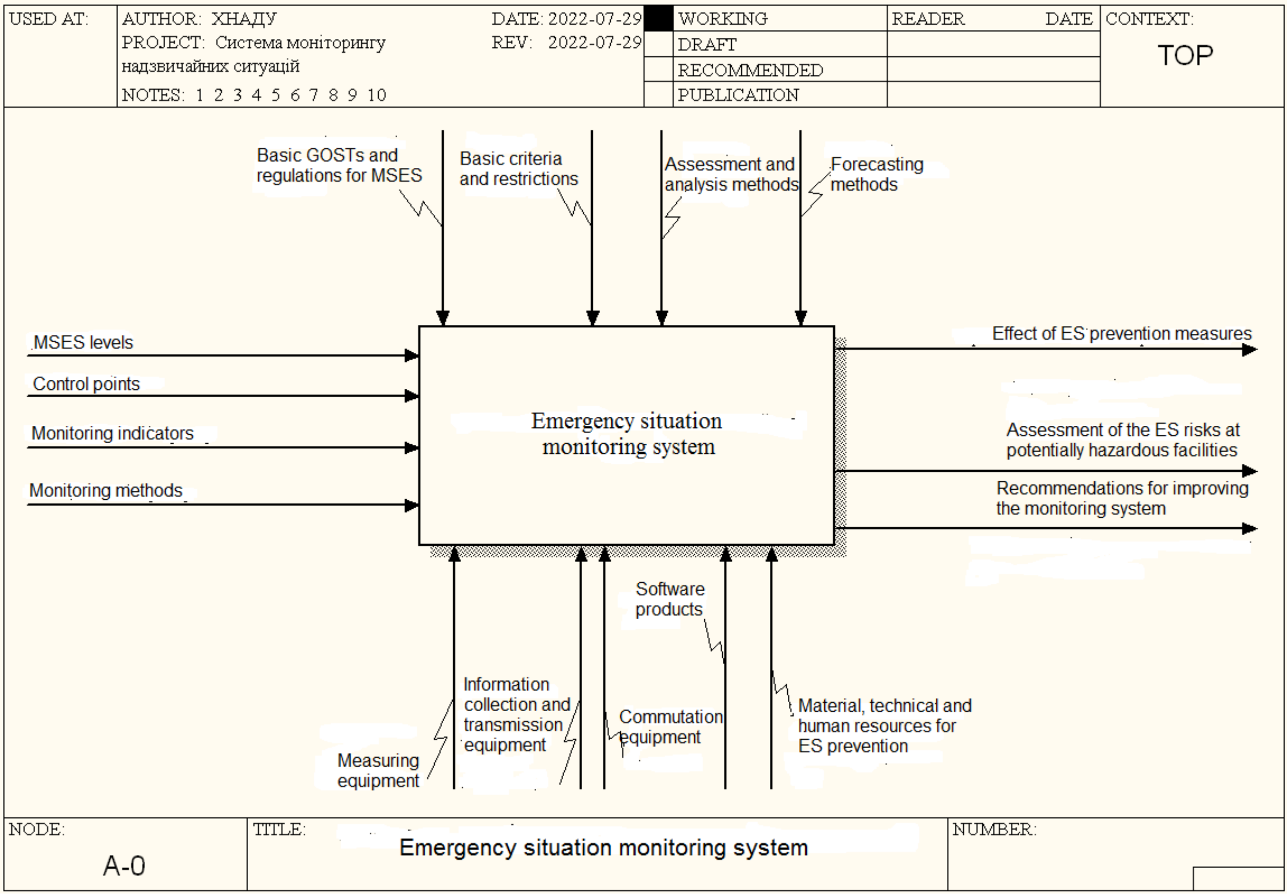

Fig. 1. Conceptual model of MSES in the form of a «black box»

At the same time, the structure of the ES monitoring system synthesis tasks is reduced to solving the following main tasks: definition of control points; selection of monitoring indicators at control points; selection of measuring devices; definition of locations of data collection and transmission devices; definition of the list of control points for each of the DCTD; selection of DCTD in each of their locations; definition of locations of control points and switching devices; definition of the list of served DCTD for each of the control units; selection of control devices for each of the control units.

The system concept of ES monitoring task interaction is presented in fig. 2. 3 presents the interaction of MSES synthesis tasks and input data for them.

The essence of tasks of structural and topological synthesis can be constructed as follows: considering sets of ordinary parts, their functions and properties, find the number of levels of the system, the set of parts on each level and their interrelations.

The task of parametric synthesis is to select the functional characteristics of elements, subsystems and links. The task is solved for specific structural, topological and technological features of the system. The results of the solution form the basis for the synthesis of elements, subsystems and links or the selection of their types and types from a given set of devices.

The MSES synthesis procedure includes a stage of analysis of the monitoring results and examination of the current situation. After that, it is possible to proceed to the selection of recommendations for the further functioning and operation of MSES.

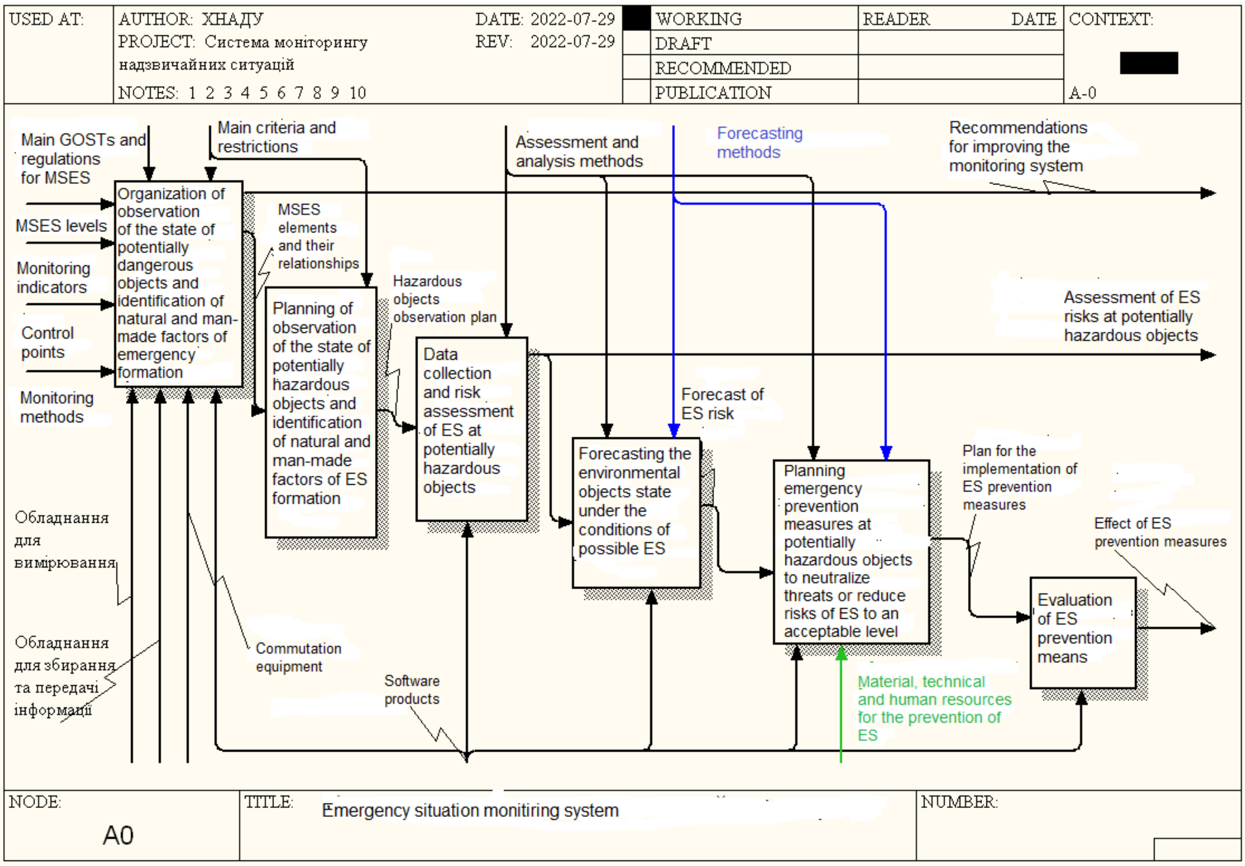

Fig. 2. System concept of interaction of ES monitoring tasks

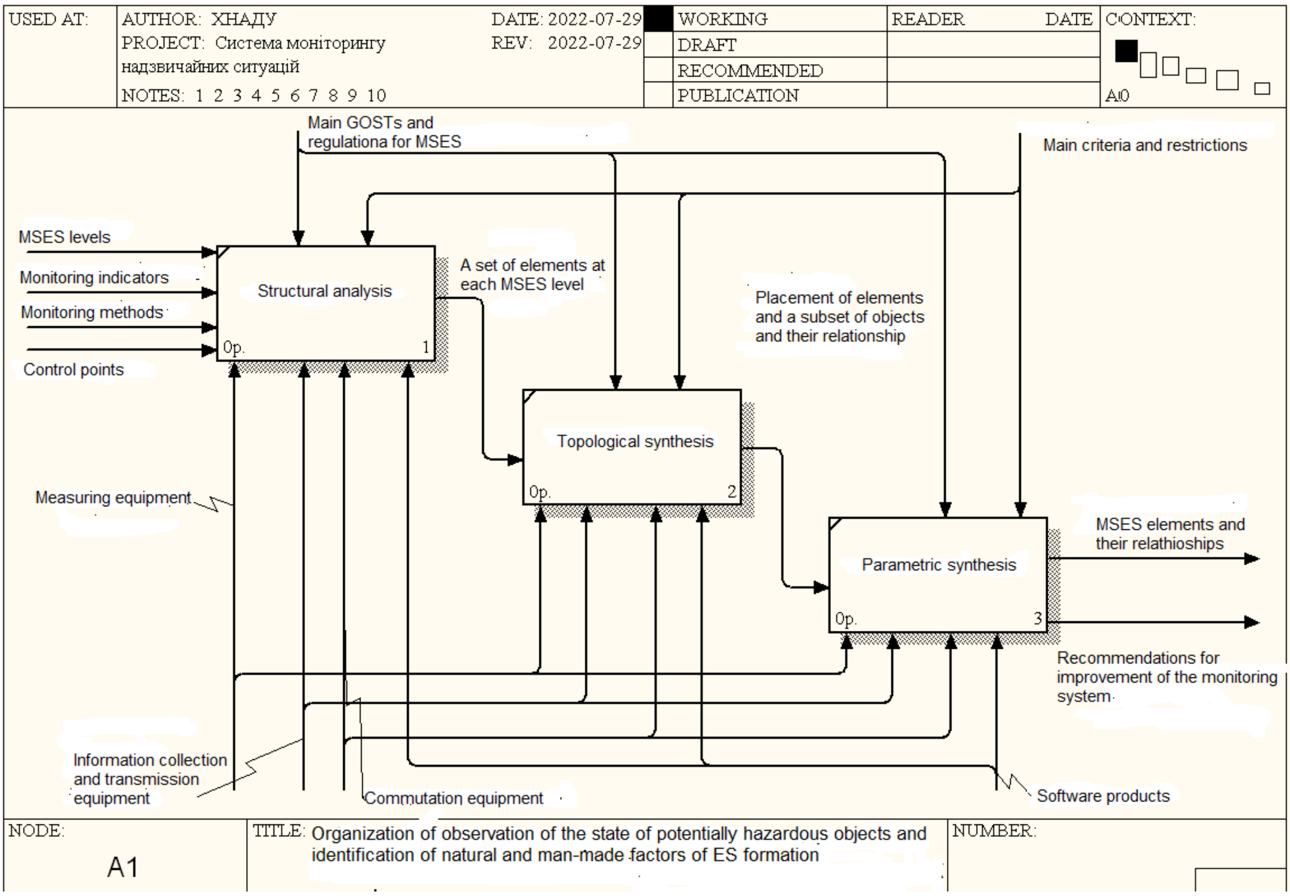

Fig. 3. Interaction of MSES synthesis tasks

Conclusion

Thus, a hierarchical structure of ES monitoring system is developed in this paper. Decomposition of ES monitoring system is proposed, which allows to define a set of tasks of MSES synthesis for each of the levels in a typical MSES. Developed a conceptual model of MSES in the form of a «black box», reflecting the interaction of input information, information, resource and methodological support to obtain initial information about the effect, the current state of the monitoring system, based on expertise, as well as receive recommendations to improve MSES. System concept of interaction tasks synthesis of ES monitoring system, which, unlike known approaches, allows to develop MSES from unified system positions. The next stage of research is to develop appropriate multi-criteria models that take into account all the features of the synthesized system.

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TECHNOLOGY OF DISTRIBUTED MANAGEMENT OF PRODUCTION PROCESSES WITH THE USE OF A SERVICE-ORIENTED APPROACH

Nevliudov I., Novoselov S.

The paper describes the technology of managing intelligent production with the use of Web services for managing distributed production processes. An analysis of the methods of implementing SOA technology in production and organization of the message exchange process was performed. The architecture of computer systems management using SOA technology and the principle of dynamic deployment of services is presented.

As a technology for the implementation of web services, it is proposed to use a distributed method of processing requests and performing services using MVC technology and the Ruby on Rails framework.

A structural diagram of the interaction of industrial equipment with the server and a generalized diagram of the organization of the web services server based on Ruby on Rails have been developed. The principle of communication between a server application and industrial equipment has been developed. The architecture of the automated production process management system using web-oriented services, taking into account the concept of Industry 4.0, was developed.

Introduction

The production process has become a collaborative activity over the years and is increasingly supported by computer systems. Thanks to joint activities, the production process has become a distributed process, where each phase of the process can be performed by different companies or individuals. This evolution became possible thanks to the development of information technologies that support the entire management process.

Currently, the production process uses several independent systems that generate a group of heterogeneous data. Managing this complex set of data involves great interoperability challenges and little flexibility, as simply changing data between systems is a challenge in itself.

Manufacturing can be understood as a set of relationships between product design, materials, production equipment and support systems, or, in short, as a set of relationships between products, processes and resources. These elements and their relationships at different levels lead to a complexity scenario, which can be seen in part as an association between understanding and managing a large body of information, which consists of three main elements: the amount of information, the variety of this information and its content, which is a measure of effort to achieve the desired result. One of the reasons for the complexity of production is the fact that data comes from different sources, generated by specific applications for each phase of product development. This leads to the need for integration between heterogeneous databases, which can be defined along three orthogonal axes: heterogeneity due to possible different interpretations; autonomy, thanks to the ability of each program to generate and manipulate data; and distribution, thanks to the location of the database components. Heterogeneous data can be managed in a variety of ways with varying degrees of distribution, flexibility, and integration.

Thus, the use of web services in production becomes more attractive because a large number of integration technologies are already used. First, Web service standards are already built into most software development tools. Second, Web services simplify engineering decisions because production applications tend to be simpler than business applications.

The relevance of research is the need to improve production systems and increase the efficiency of the functioning of industrial facilities in order to achieve high final results of activities based on the rational use of production resources.

Service-oriented approach in production management

A service-oriented approach in production management allows for the distribution of data in isolated applications, but the construction of a central model must be performed through weak links. Thus, the characteristic of autonomy of data management for each application is preserved, and the central model remains harmonious [1]. This intermediate solution not only preserves the independence of each program, but also forces each part to cooperate with the whole according to its specific capabilities. This approach allows you to insert the data of the legacy system into the central model only by creating a data adjustment interface, without the need to modify the model as a whole.

Thanks to these characteristics, this model represents the greatest flexibility without losing its characteristics of integration and distribution. The implementation of this model involves a separation layer that can request information from distributed databases, creating an interface between the partial models and the central model. A distributed data model is a solution to the integration of partial models that exist in manufacturing activities, as it meets both the requirements of distribution and integration while maintaining a high level of flexibility.

Analysis of methods of implementing SOA technology in production

The number and complexity of information systems used in companies is growing, business requirements for them are also growing, and modernizing computer-integrated systems (CIS) is becoming more and more difficult and expensive. A contradiction arises: frequent changes in business processes require IT specialists to implement them as quickly as possible, but from the point of view of economic efficiency, the cost of owning a CIS must be minimized.

Thus, for process-oriented management, a tool is needed, with the help of which it would be possible not only to effectively manage processes, but also to ensure the adaptability of CIS to changes in processes with minimal costs and in the shortest possible time. After all, one-time solutions and «patches» lead to the «hardening» of the IT solution – and, therefore, the business processes of the company, which negatively affects the overall efficiency of the business [2].

Service-oriented architecture (SOA) solves the task of increasing the flexibility of CIS, reducing the cost of software development, increasing the speed of response to changing business requirements, and also ensuring the necessary level of integration between information systems.

Figure 1 shows the control architecture of the CIS using SOA technology [3, 4].

With this approach, a general idea of the enterprise's IT architecture is created on the basis of top-level process models, which first of all implies the definition of the main types of IS that will be used. Further description of processes, at lower levels of detail, will allow to determine the main models or groups of services that will be needed to support business processes. The description of processes at the workplace level will determine the necessary functionality for services (the so-called «mapping») between business process functions and IT system services, and in the absence of the necessary service, it is necessary to formulate requirements for its development and create it.

The process organization depicted in Figure 1 implies the composition of web services to enable the execution of a complex process. This composition can be supported by BPEL. Figure 1 defines a service management architecture that has three main elements: a manager, service-oriented middleware, and a decision execution system (DSS). The manager is the main element that allows the discovery and definition of services for use by the system. In addition, it ensures the approval of service compositions. The role of the manager is to check, if the implementation of this program is possible, then the list of available services is determined. The manager deploys the management mechanism to the middleware service level.

One of the main principles of activity improvement is the reuse of previously obtained results, including software code. At one time, the repeated use of once developed functions and procedures (structural programming) was widely used.

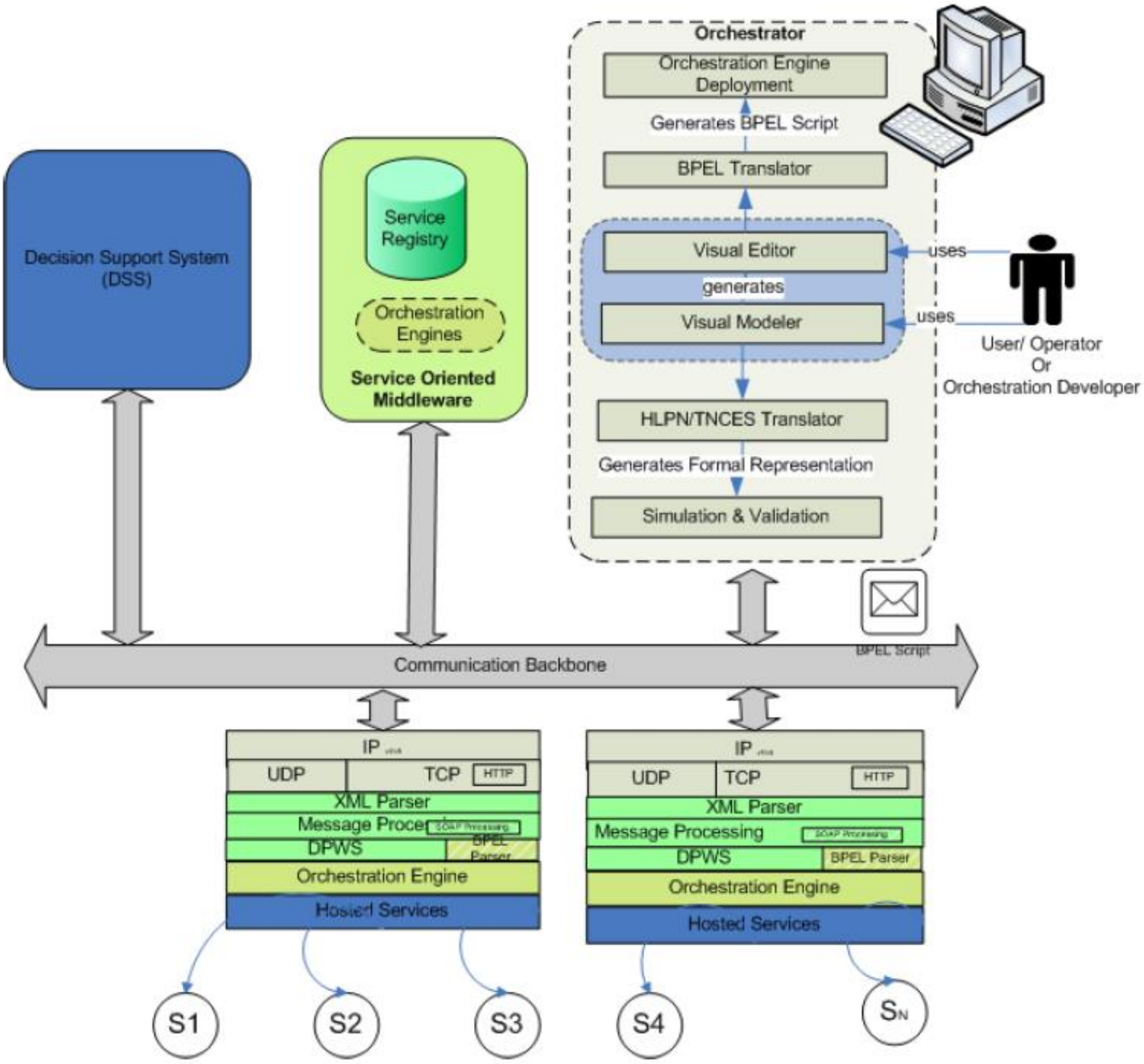

Fig. 1. CIS management architecture using SOA technology

SOA offers the principles of a process-oriented approach to building IT solutions. The developer of the IT solution formalizes the business process and connects to it typical services from the library, after which the resulting solution is transferred for execution. This approach minimizes code development. If it is necessary to make changes to the process, it is enough to change its logic without affecting the functionality of the services, which significantly speeds up the implementation of changes.

Mathematical modeling of the decentralized system

We assume that the system functions under normal conditions, therefore, the independence of individual failures can be assumed. In the proposed model, the subsystem is non-renewable.

A decentralized computing system will be understood as a set of hardware and software tools that implement the following basic functions: data processing, storage, transmission, and protection [5].

The following types of security system failures can be distinguished: hidden and false. In the event of a hidden failure of the security system, it does not respond to the failure of other subsystems, in the event of an erroneous operation, the security system involuntarily produces protective functions during the normal operation of the data storage system, data processing system, data transmission system and causes the system to stop.

The main indicator of reliability will be the probability of data loss over a certain time interval. Data loss means real destruction, data leakage, or the impossibility of accessing them for a sufficiently long period of time.

Figure 2 shows a graphic model of the functioning of RSK nodes, which reflects the failure of its subsystems and the further development of the situation.

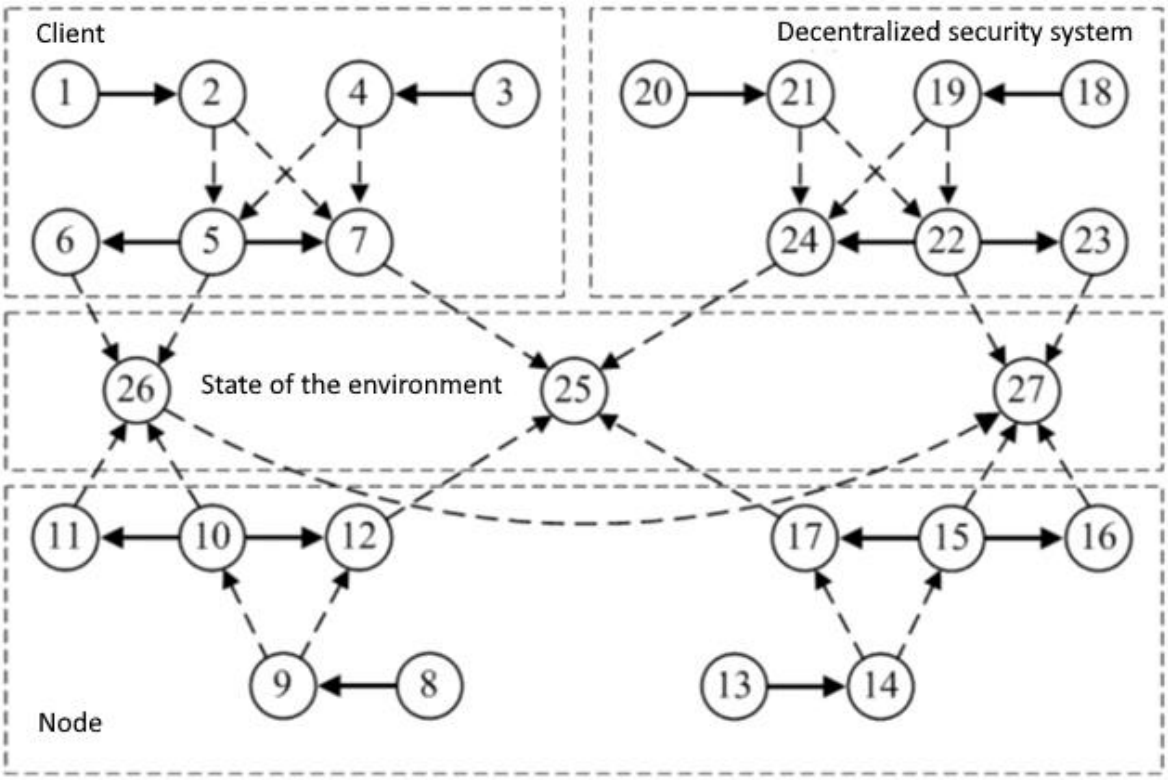

Fig. 2. Graphical model of functioning of the decentralized computing system

Solid lines indicate element transitions, dashed lines indicate the development of element failure situations. The numerical symbols in the figure mean the following:

1. Normal operation of the data processing system.
2. Data processing system failure.
3. Normal operation of the client's data transmission system.

4. Failure of the client's data transmission system.

5. Normal operation of the client's security system.

6. False failure of the client's security system.

7. Hidden failure of the client's security system.

8. Normal operation of the node of the data transmission system.

9. Failure of the node of the data transmission system to which the client is connected.

10. Normal operation of the security system node port to which the client is connected.

11. False failure of the node of the security system to which the client is connected.

12. Hidden failure of the node of the security system to which the client is connected.

13. Normal operation of the node of the data processing system.

14. Failure of a data transmission system node.

15. Normal operation of the security system node.

16. False failure of the security system node.

17. Hidden failure of the security system node.

18. Normal operation of the data storage system.

19. Failure of the data storage system.

20. Normal operation of the node of the data transmission system.

21. Failure of a data transmission system node.

22. Normal operation of the security system node.

23. False failure of the security system node.

24. Hidden failure of the security system node.

25. Decentralized computer system crash status.

26. The state of reduced efficiency of the decentralized computing system.

27. Decentralized computer system stop state.

In case of failure of the data processing system or data transmission system on the client or the failure of a node of the data transmission system to which the client is connected, with the normal operation of the corresponding security system, the client or node goes into a stop state, and the system itself goes into a state of reduced efficiency (as in the case of a false failure of a client security system or a node In the event of a storage system or data communication system failure with the corresponding client security system operating normally, the decentralized computing system enters a halt state, as well as in the event of a false failure of the security system node to which it is connected, and also in the event of the shutdown of all clients or the nodes to which the clients are connected.

If any of the subsystems fail in case of a hidden failure of the security system, the system goes into an emergency state.

We will consider the behavior of the system on the interval $[0,\ t]$. Let's enter the necessary notation:

1. Let ψ – be the failure response of a data processing system with distribution $f(t)=P(\le t)$.

2. δ – failure recovery of a distributed data storage system $f(t)=P(\le t)$.

3. $\gamma_1, \gamma_2, \gamma_3$– working time for failure of the client, nodes and nodes of the security system, respectively, having a distribution $F_1(t)=P(\gamma_1 \le t)$, $F_2(t)=P(\gamma_2 \le t)$, $F_3(t)=P(\gamma_3 \le t)$.

4. Let us denote as p_1, p_2, p_3 – the run-up to a hidden failure, and as – the run-up to η_1,η_2,η_3 a false failure of the client, nodes and nodes of the security system with the corresponding distributions:

$$F_{p1}(t)=P(p_1 \le t),$$
$$F_{p2}(t)=P(p_2 \le t),$$
$$F_{p3}(t)=P(p_3 \le t),$$
$$F_{\eta 1}(t)=P(\eta_1 \le t),$$
$$F_{\eta 2}(t)=P(\eta_2 \le t),$$
$$F_{\eta 3}(t)=P(\eta_3 \le t).$$

Reliability indicators mean the probabilities of the system transitioning into a state of stoppage and breakdown, as well as the intensity of these transitions. A shutdown of a distributed computing system will occur if all clients of the node to which the clients, security nodes, or port of the data processing node are connected enter the shutdown state.

The probability that a stop will occur in the interval $[0,\ t]$ can be written in the following form:

$$P_0(t)=1-M\left(\overline{P_{зк1}}(t)\overline{P_{зк2}}(t)\overline{P_{зк3}}(t)\right), \tag{1}$$

where $\overline{P_{зк1}}$ – the probability of stopping all customers at time t,

$\overline{P_{зк2}}$ – the probability of stopping all nodes to which clients are connected at time t,

$\overline{P_{зк1}}$ – the probability of stopping the decentralized SS at time t.

Auxiliary variables should be entered. Let ζ_i – be the time until the i -th client stops, where $i=\overline{1,N}.$ Then the probability that all customers will stop in the interval $[0,\ t]$ is determined as follows:

$$P_{зк1}(t)=P\left(\vee_{i=1}^{N}\zeta\le t\right), \tag{2}$$

where $\vee_{i=1}^{N}\zeta_i\le t=\ \max(\zeta_1,\zeta_2,\ldots,\zeta_N)$.

Using the properties of indicators and mathematical expectation, we get:

$$\begin{gathered}P_{зк1}(t)=MI_{\vee_{i=1}^{N}\zeta_i\le t}=M\prod_{i=1}^{N}I_{\zeta_i\le t}=\prod_{i=1}^{N}MI_{\zeta_i\le t}=\\=\prod_{i=1}^{N}P(\zeta_i\le t)=\prod_{i=1}^{N}\left(1-\overline{P_{iзк}}(t)\right),\end{gathered} \tag{3}$$

where $\overline{P_{iзк}}(t)$ – the probability that the i -th client will not stop at time t ;

$\zeta_i\le t$ – indicator function $\left(I_{\zeta_i}\le t=1\ at\ \zeta_i\le t\ \&\ I_{\zeta_i}=0\ at\ \zeta_i>t\right).$

The probability that the i -th client at time t will not go into the stop state:

$$\begin{aligned}&\overline{P_{iзк}}(t)=P\left(I_{p_{1i}\ge\psi_i\wedge\gamma_{1i}}\psi_i\wedge\gamma_i\wedge\eta_{1i}+I_{p_{1i}<\psi_i\wedge\gamma_{1i}}\eta_{1i}>t\right),\\&\psi_i\wedge\gamma_{1i}=\min(\psi_i,\gamma_{1i}).\end{aligned} \tag{4}$$

Development of a Web server structure for messaging in a distributed production management system

Taking into account the analysis of technologies for creating web-oriented services, it is possible to create a server structure to implement the given task.

The client communicates with the server via the HTTP protocol. The basis of this protocol is a request from the client to the server and a response from the server to the client. For requests, generally GET methods are used if we want to get data and POST if we want to publish, if we want to change data. The request is also specified in the request, the request body (if it is a request) and a lot of additional technical information [5, 6, 7].

Figure 3 shows a generalized scheme of the web services server based on Ruby on Rails.

When a request arrives at the server, it does not immediately enter the ROR. First, it is handled by the Nginx web server. If a static file (such as a file or image) is requested, Nginx itself sends it back to the client. If the request is not static, then Nginx should continue (pass) to the ROR.

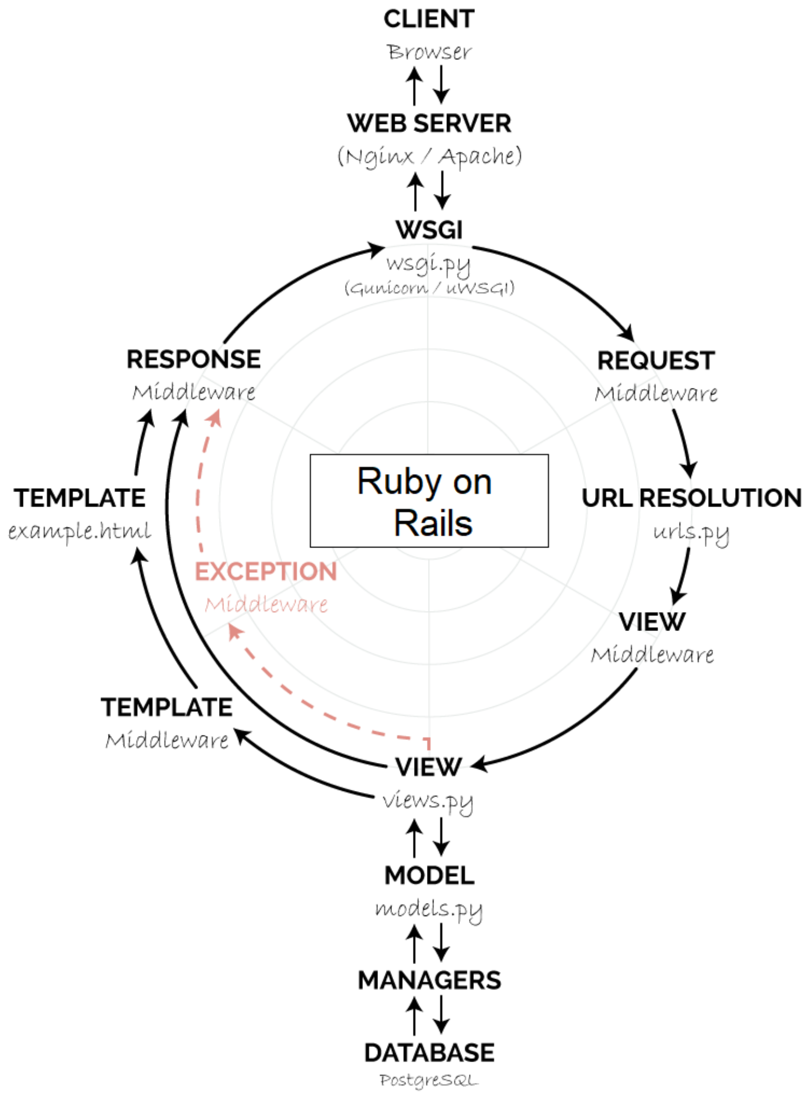

Fig. 3. Generalized scheme of the web service server organization based on Ruby on Rails

After the ROR has processed the request, it returns a response to the client in the form of HTML or a dataset and response code. If everything is fine, the response code is 200, if the page is not found, it is 404, and if an error occurred and the server could not process the request, then it is 500.

Figure 4 shows the structural diagram of the interaction of industrial equipment with the server.

In the diagram (Figure 4), industrial equipment (robot), CNC machine tool, executive device are clients of web services serving the industrial site [8]. In relation to the server, they are equal, that is, the server responds to their requests in the same way. All client devices send requests containing certain data to the server and receive responses with generated data that match the request.

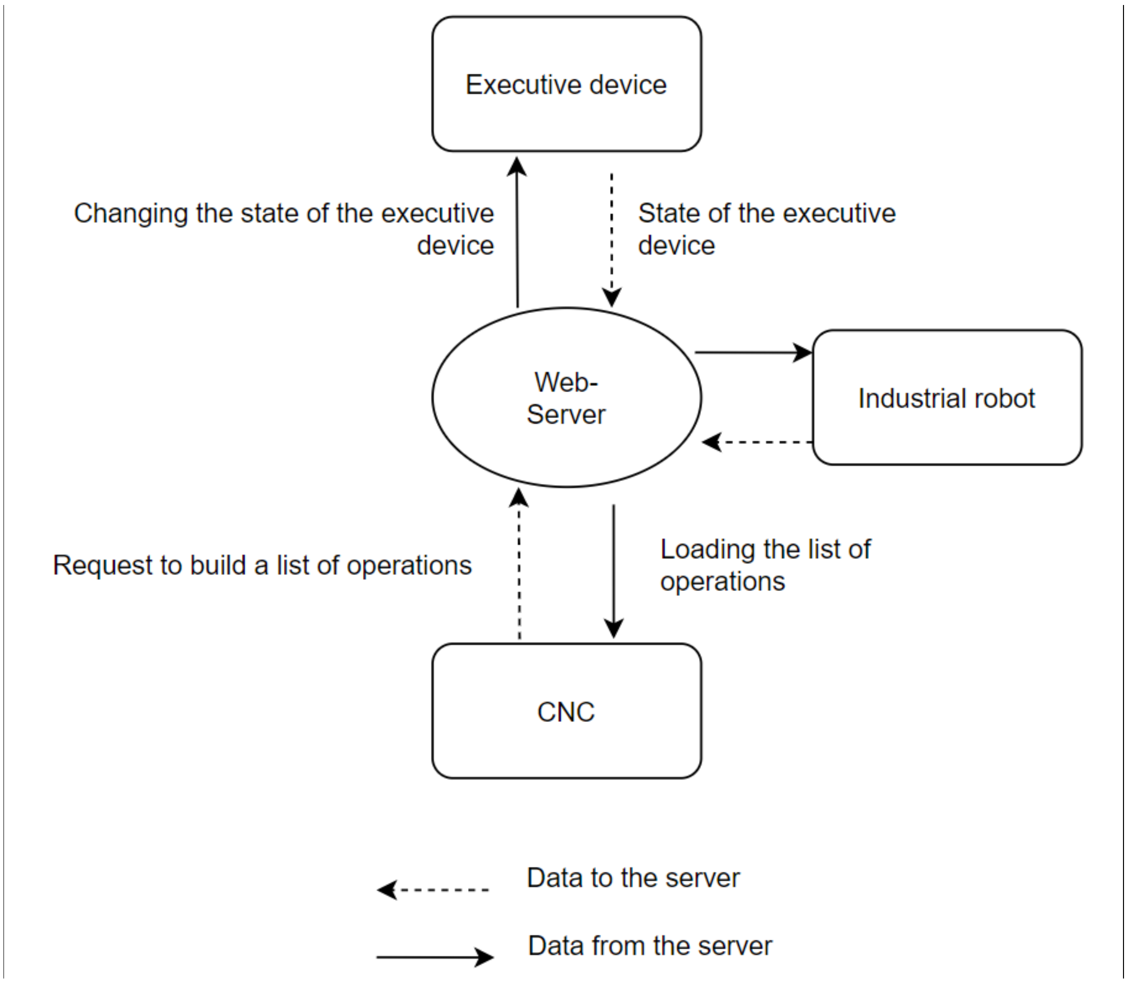

Fig. 4. Structural diagram of interaction of industrial equipment with the server

The main components that make up the server are shown in the diagram in Figure 5.

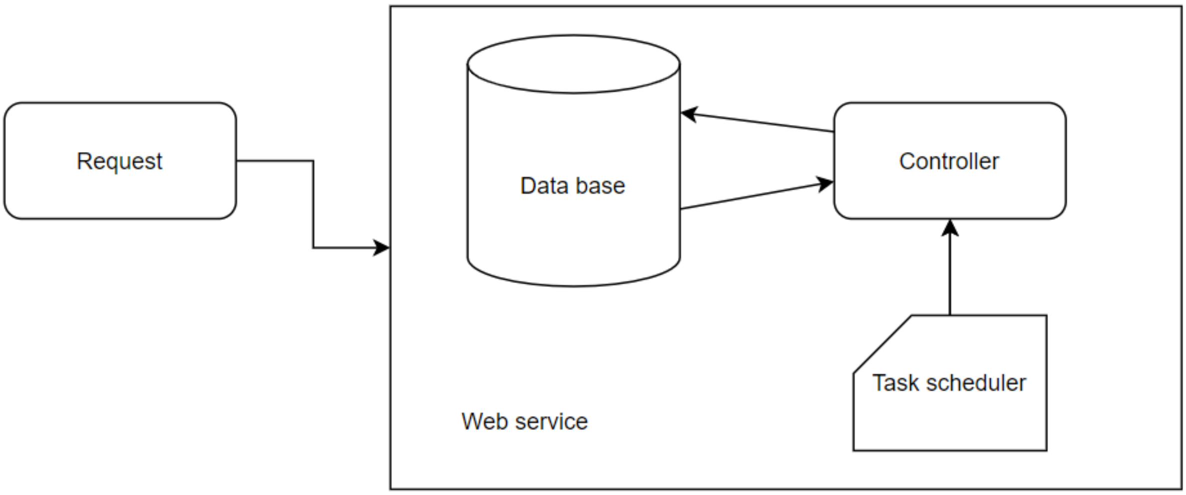

Fig. 5. The main components that make up the server

A web services server is a dedicated computer on which special software with support for the HTTP protocol is installed, with the help of which it exchanges information with its clients.

In addition, the server must have a database, task scheduler and server scripts.

Development of server software architecture

The concept of IoT, in relation to industrial automation, found its expression in the concept of Industry 4.0 [9]. «Smart factories» are characterized by the presence of cyber-physical systems: embedding computing elements (together with software and network capabilities) into physical control objects.

Taking into account this concept, the informational interaction of various types of devices and installations is an integral condition for the functioning of almost any production. This technology is called machine-to-machine interaction (M2M) and closely overlaps with IoT. In essence, IoT is a key component of the emerging Industry 4.0 concept, which involves the exchange of data between all actors involved in the production chain:

– specialists of the enterprise;

– executive components;

– ERP systems;

– robots;

– products and other systems and installations.

Let's consider the components of the production area:

– an intelligent vehicle;

– intelligent machine;

– data transfer environment;

– cloud data storage.

An intelligent vehicle has the following capabilities:

– always maintains a connection with the cloud;

– downloads the manufacturing technology of one or another part from the cloud;

– determines the trajectory of movement to the required equipment;

– checks the availability of the equipment for the next technological operation;

– moves parts between equipment;

– moves parts to temporary storage.

The intelligent machine has the following capabilities:

– a set of sensors determines the state of the main components of the equipment;

– the data transfer tool transmits information about the current state of the equipment and the stage of manufacturing the part to the cloud;

– the internal controller controls the mechanisms of the device and takes readings from the sensors;

– processes the received part according to the given technology;

– informs about the completion of the processing of the part.

Taking into account the above, the architecture of the automated production process management system using web-oriented services was built (Figure 6) [10, 11].

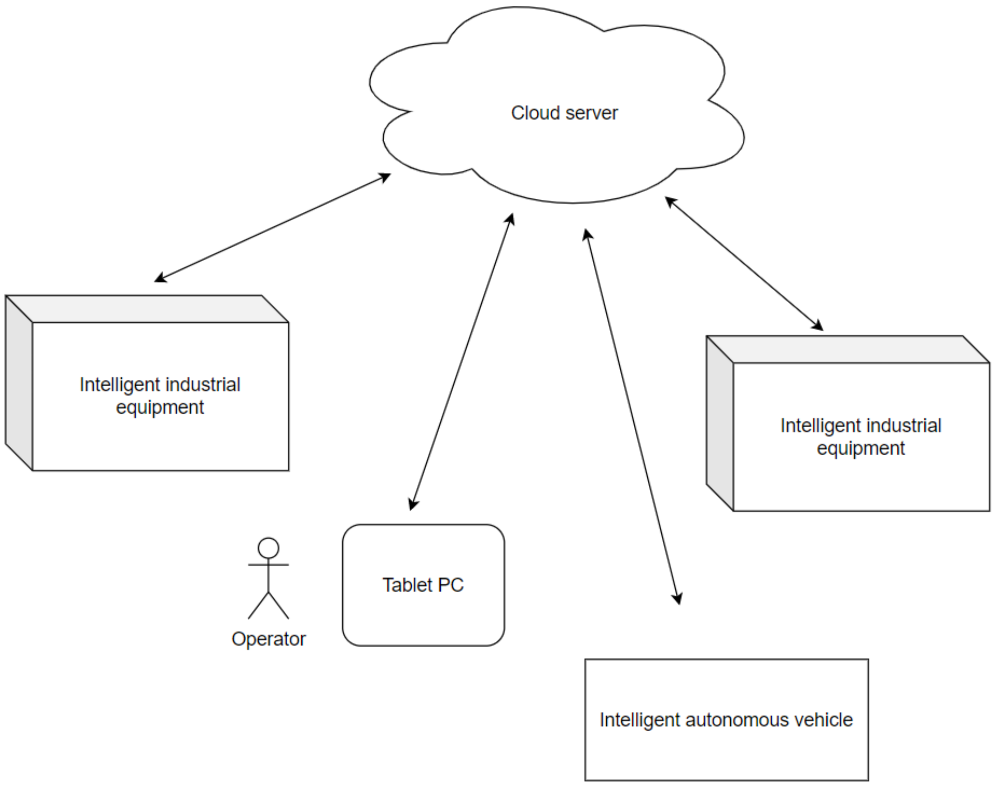

Fig. 6. Architecture of an automated production process management system using web-based services

The data transmission environment is built using wireless technology to implement the principle of mobility and scalability [12]. A simplified network protocol working on top of TCP/IP is used as a data exchange protocol for the exchange of messages between devices according to the publisher-subscriber principle.

Based on the above, we formulate the characteristics of the behavior of the production site, which is built according to the requirements of the Industry 4.0 concept:

– flexible reconfiguration of the technological process;

– easy scalability (depending on the current production load, equipment can be quickly added or removed. Each new equipment informs itself of the necessary parameters and capabilities through inter-machine communication. Depending on the received information, the behavior of the entire site changes, and intelligent transport changes the route of the delivery of blanks and transportation of semi-finished products , as well as products);

– interaction between production equipment and intelligent transport is carried out using wireless data exchange protocols;

– storage of information about equipment loading, properties of each machine, its throughput, the general state of the technological process of manufacturing parts and the current state of each individual part is stored in a public cloud on a dedicated server;

– it is possible to simultaneously manufacture several parts using different technological processes (provided the equipment nomenclature is sufficient).

To build the server, the MVC (Model – representation – controller) technology is used – an architectural template used during the design and development of software [11].

Figure 7 shows the construction architecture of the developed server.

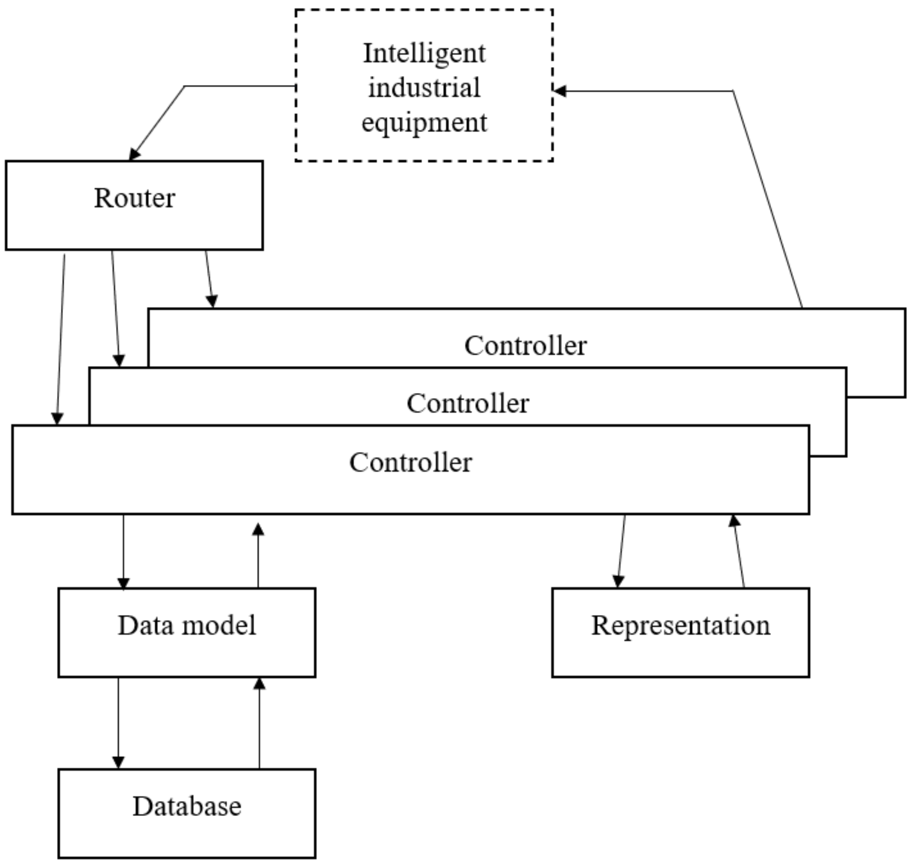

Fig. 7. Construction architecture of the server under development

Interacting with the web application of the server, the intelligent production equipment sends a request, which is accepted by the server and transmitted to the appropriate controller responsible for the chosen method. After calling the model, the controller then renders the view and returns a JSON response. By default, Rails uses the ActiveRecord library to store model objects in the relational DBMS. A competing analogue is DataMapper. The PostgreSQL relational database is used as a database. The software tool includes four controllers for processing messages from the user.

Conclusion

This work describes the technology of distributed management of production processes using a service-oriented approach. An analysis of modern technologies for deploying web services has been carried out. An analysis of the methods of implementing SOA technology in production and the organization of the message exchange process was performed. The architecture of computer systems management using SOA technology is presented. Mathematical modeling of the decentralized system was performed. As a result of the performed analysis, it is shown that the main indicator of the reliability of such a system is the probability of data loss for a certain time interval. A structural diagram of the interaction of industrial equipment with the server and a generalized diagram of the organization of the web services server based on Ruby on Rails have been developed. The principle of communication between a server application and industrial equipment has been developed. The architecture of the automated production process management system using web-oriented services, taking into account the concept of Industry 4.0, was developed.

Thus, the use of web services in production is more attractive because a large number of integration technologies are currently used and in the future even more use of intelligent devices with the use of computer-integrated control technologies is expected.

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CHOICE OF INFORMATIVE ATTRIBUTES FOR MONITORING OF THE ELECTRONIC COMPONENTS OF AUTOMATICS LIFECYCLE

Nevliudov I., Andrusevich A., Starodubcev N., Demska N., Vzhesnievskyi M.

The methods of identification of ECA states, the distinctive attribute of which is to provide the formulation of the rule of division of sets in the space of states and the rules establishing correspondence between the sets of parameters and values of performance indicators of ECA LC, the application of the mentioned rules makes it possible to build and control algorithms of optimization of indicators of ECA LC. The methods of solving the problems of selecting the informative attributes of ECA and display monitoring as a process of ECA LC, which are distinguished by the use of geometric interpretation, consideration of selection problems in the feature space, and therefore the visualization of the analysis and optimization processes are considered.

Introduction

A distinctive attribute of electronic components of automatics (ECA) is the presence of a large number of monitored parameters. Monitoring, which provides the ability to measure and record the values and rates of change of ECA parameters, may have additional capabilities, giving an idea of the state of ECA under a multitude of parameters as a statistical ensemble. It is known in science when description of behavior of micro ensemble of particle parameters gives possibility to determine macroparameters of systems, create phenomenological theory and use for estimation and management of state of such systems. An example is a physical medium consisting of atoms and molecules, micro-parameters here are coordinates and impulses of these particles, phenomenological theory is thermodynamics, macroparameters are volume, pressure, temperature, etc. The observation, in the field of view of which the phase plane on which the decay and mixing of the statistical ensemble of ECA parameters can be observed, provides additional opportunities for monitoring the life cycle (LC) of ECA.

It is known [1–3] that the functional problem of selecting informative attributes for monitoring ECA LC, as well as reducing their list, reducing uncertainty can be solved within the methodology of developing a dictionary of features in systems of classification and recognition of the state of objects. Here the purpose of the selection is to provide optimal recognition. The working dictionary should use only the features that, on the one hand, are the most informative and, on the other hand, can be available (for example, in terms of costs) for measurement.

The definition of the dictionary of features under the constraints on the cost of the creation of technical means of observation has peculiarities.

If we denote the features of objects by δ_j, $j = 1, 2, ..., N$, then each object in the N-dimensional feature space can be represented as a vector $x = (x_1, x_2, ..., x_N)$, which coordinates characterize the properties of objects.

To determine the measure of proximity or similarity between objects in the N-dimensional feature vector space, a metric is introduced. One can use the Euclidean metric

$$d^2(w_{pk}, w_{ql}) = \sum_{j=1}^{N} \left(x_{pk}^{j} - x_{q_l}{}^{j} \right)^2, \tag{1}$$

$$p, q = 1, 2, ..., m; \quad k = 1, 2, ..., k_p; \quad l = 1, 2, ..., k_q,$$

where x_{pk}^{j} – are the values of the j-th feature of the k-th object of the p-th class, i.e. the object of the q-th class, i.e. the object w_{ql}.

As a measure of proximity between objects of a given class Ω_p, $p = 1, 2, ..., m$, we will use the value

$$S(\Omega_p) = \sqrt{\frac{2}{k_p} \frac{1}{k_{p-1}} \sum_{k=1}^{k_p} \sum_{l=1}^{k_p} d^2(w_{pk}, w_{pl})}, \tag{2}$$

which has the meaning of the root-mean-square scatter of the class or the root-mean-square scatter of the objects within the class Ω_p, as a measure of proximity between objects of a given pair of classes Ω_p and Ω_q, $p, q = 1, ..., m$, – value

$$R(\Omega_p, \Omega_q) = \sqrt{\frac{1}{k_p k_q} \sum_{k=1}^{k_p} \sum_{l=1}^{k_q} d^2(w_{pk}, w_{ql})}, \tag{3}$$

which has the meaning of the root-mean-square scatter of objects of classes Ω_p and Ω_q.

The set of features used in the working dictionary can be described by an N-dimensional vector $\mathrm{A} = (\alpha_1, \alpha_2, ..., \alpha_N)$, whose components take values 1 or 0, depending on whether it is possible or impossible to determine the corresponding feature of the object.

Taking into account α the square of the distance between two objects w_{pk} and w_{ql}

$$d^2(w_{pk}, w_{ql}) = \sum_{j=1}^{N} \alpha_j \left(x^{(j)}{}_{pk} - x^{(j)}{}_{ql} \right)^2. \tag{4}$$

Consequently, the root-mean-square scatters of class Ω_p and objects of classes Ω_p and Ω_q can be written as

$$S\left(\Omega_p\right)=\sqrt{\frac{2}{k_p}\,\frac{1}{k_p-1}\sum_{k=1}^{k_p}\sum_{l=1}^{k_p}\sum_{j=1}^{N}\alpha_j\left(x^{(j)}{}_{pk}-x^{(j)}{}_{pl}\right)^2}\,, \tag{5}$$

$$R\left(\Omega_p,\Omega_q\right)=\sqrt{\frac{1}{k_p}\,\frac{1}{k_q}\sum_{k=1}^{k_p}\sum_{l=1}^{k_q}\sum_{j=1}^{N}\alpha_j\left(x^{(j)}{}_{pk}-x^{(j)}{}_{pl}\right)^2}\,. \tag{6}$$

It can be assumed that the costs of using a feature are proportional to their informativeness, i.e., to the number of features of objects that can be determined with their help. This assumption (leaving aside the question about the accuracy characteristics of observation means) is quite general.

Thus, the costs of using the features

$$C=C\left(\alpha_1,...,\alpha_N\right)=\sum_{j=1}^{N}C_j\,\alpha_j\,, \tag{7}$$

where C_j – costs of determining the j-th feature.

As an indicator of quality or efficiency of the designed recognition system, consider a function that depends in the general case of the function $S\left(\Omega_p\right)$, $R\left(\Omega_p,\Omega_p\right)$ of the decisive rule $L\left(w,\left\{w_g\right\}\right)$

$$I=F\left[S\left(\Omega_p\right);\ R\left(\Omega_p,\Omega_q\right);\ L\left(w,\left\{w_g\right\}\right)\right]. \tag{8}$$

Let the value $L\left(w,\left\{w_g\right\}\right)$ be a measure of proximity between a recognizable object w and a class Ω_g, $g=1,\ 2,\ ...,\ m,$ given by its objects $\left\{w_g\right\}$. As this proximity measuree, let us consider the value

$$L\left(w,\left\{w_g\right\}\right)=\sqrt{\frac{1}{k_g}\sum_{g=1}^{k_g}d^2\left(w,w_g\right)}\,, \tag{9}$$

which is the root-mean-square distance between the object w and the objects of the class Ω_p.

The decisive rule is as follows $w\in\Omega_g$, if

$$L\left(w,\left\{w_g\right\}\right)=extr\,L\left(w,\left\{w_i\right\}\right). \tag{10}$$

It is important to note that the reduction of the value $S\left(\Omega_p\right)$, «compression» of objects belonging to each given class, with a simultaneous increase of $R\left(\Omega_p,\Omega_q\right)$, i.e. «dilution» of objects belonging to different classes provides, ultimately, an improvement in the quality of the recognition system. Therefore we will connect the increase of the efficiency of the system with the achievement of the extremum of the functional I.

Statement of the research problem

The statement of the research problem can be formulated as follows.

Let the set of objects be subdivided into classes Ω_i, $i=1, ..., m$, all classes are described a priori in the language of features x_j, $j=1, ..., N$, and funds equal to C_0 are allocated for the creation of technical means of observation. It is required, without exceeding the allocated amount of funds, to construct a working dictionary of attributes that provides the highest possible efficiency of the system.

Thus, the problem is reduced to finding a conditional extremum of a functional of the form (8), i.e. to determining A implementing

$$\underset{\alpha}{extr}\, I = \underset{\alpha}{extr}\, F\left[S\left(\Omega_p\right);\; R\left(\Omega_p,\Omega_q\right);\; L\left(w,\left\{w_g\right\}\right)\right]$$

$$C = \sum_{j=1}^{N} C_j\alpha_j \le C_0 . \tag{11}$$

Possible kinds of the functional. Let us consider some particular kinds of the functional (11). If the required efficiency of the recognition system can be achieved by a more compact arrangement of objects of each class under some conditions concerning the value of $R\left(\Omega_p,\Omega_q\right)$, then the problem is reduced to finding

$$\min_{\alpha}\ \max_{i=1,...,m}\left[S\left(\Omega_i\right)\right] \tag{12}$$

at

$$\sum_{j=1}^{N} C_j\,\alpha_j \le C_0 \text{ and } R\left(\Omega_p,\Omega_q\right) \ge R_0^{(pq)}. \tag{13}$$

If the required efficiency of the system can be achieved by «removing» from each other objects belonging to different classes under certain conditions regarding the value of $S\left(\Omega_i\right)$, $i=1,\dots,m$, then the problem is reduced to finding

$$\max_{\alpha}\ \min_{p,q=1,...,m}\left[R\left(\Omega_p,\Omega_q\right)\right] \tag{14}$$

at

$$\sum_{j=1}^{N} C_j \alpha_j \le C_0 \text{ and } S\left(\Omega_i\right) \le S_0^i . \tag{15}$$

If the proper efficiency of the system can only be achieved by increasing the ratio of distances between classes to the rms scatter of objects within classes, then the problem is reduced to finding

$$\max_{\alpha} \min_{p,q=1,\ldots,m} \left[\frac{R^2\left(\Omega_p\ \Omega_q\right)}{S\left(\Omega_p\right) S\left(\Omega_q\right)} \right] \tag{16}$$

at

$$\sum_{j=1}^{N} C_j \alpha_j \le C_0 . \tag{17}$$

Solving the problem of selecting informative attributes that characterize the state of ECA LC processes

The problem considered above is a generalization of the nonlinear programming problem. The optimality conditions for it can be formulated as follows: for the vector C^0 to be an optimal strategy, it is necessary that there exist a scalar $\beta \ge 0$ and a vector $\mu = \{\mu_1, \ldots, \mu_n\}$ such that

$$\left.\begin{aligned}
&\left[\sum_{r=1}^{n} \mu_r \rho_r^j\right] \frac{dP_j\left(C_j^0\right)}{dC_j} = \beta, \quad j = 1, \ldots, N_p; \\
&\sum_{j=1}^{N_p} C_j^0 = C_0; \\
&\sum_{r=1}^{n} \mu_r = 1,\ \mu_r = 0, \text{ if } \sum_{j=1}^{N_p} \rho_r^j P_j\left(C_j^0\right) > W\left(C^0\right).
\end{aligned}\right\} \tag{18}$$

The introduction of a scalar β and a vector μ increases the number of unknowns C_j^0, μ_r and β to the value $N_p + n + 1$. However, the number of equations equals the number of unknowns, since for any *r* either $\mu_r = 0$, or

$$\sum_{j=1}^{N_p} \rho_r^j P_j\left(C_j^0\right) = W\left(C^0\right). \tag{19}$$

Thus, the solution of the system of equations (18) makes it possible to determine the composition of the features of the working dictionary and the optimal allocation of costs for the creation of recognition system observation tools under the assumption of dependence $P_j = P_j\left(C_j\right)$ and limitations on the total value of these means.

With the limitations associated with the possibility of using the entire dictionary of features, the task of selecting a limited list (up to 2–3 features) arises. Here it is possible to be guided by the location of the individual components of the feature vector relative to the boundaries of the serviceability area of the monitoring objects.

Since at the boundary value of the parameter $y_{гр}^{j}$, the end of vector X must be at the boundary of the serviceability area, it is necessary that the equality is fullfilled

$$x_{гр}^{i} = a_j^i y_{гр}^{j}. \tag{20}$$

In statistical estimation, the correlation coefficient r_{ij} between the parameters can serve as an additional criterion for selection. Since the maximum correlation coefficient provides the maximum amount of information

$$J\left(y^j\right) = H\left(y^i\right) - H\left(y^j / y^i\right), \tag{21}$$

contained in the parameter y^i. Here $H\left(y^i\right)$ – initial entropy; $H\left(y^j / y^i\right)$ – conditional entropy of the object after measuring the parameter y^j.

The use of binary correlation algorithms makes it possible to formalize and automate the processes of input, processing and recognition of the resulting image with the participation of the decision maker (DM).

ECA LC process state identification

Identification of ECA LC assumes the existence of rules that define the states of ECA. The attributes that allow to distinguish the states of the object being monitored are the performance indicators, which for the allocated state will have a given or extreme value. In order to identify the states of ECA in the monitoring process, it is necessary to check whether the observed parameters are those that provide the performance criteria, whether they belong to the set, on which the value of the performance indicators will have set or extreme values. Methods of functional analysis [4, 5] can be used to solve the problems of state estimation.

Objects of observation – parameters and characteristics of ECA can be considered as points of vector and functional spaces. For all possible pairs of points at a set Q, there exists a binary relation of comparative efficiency: a point x is more efficient than y when and only when $(x, y \in \Phi)$ or in another notation $x \Phi y$. When ECA LC is provided, the problem of kernel extraction – the set of maximal elements from X by the binary relation $\Phi : X^* = Max(Q, \Phi)$. It is assumed that the solution of the problem exists, i.e. the set X^* is not empty. In many problems we can assume that the solution – set X^* – consists of a single element, and the relationship between the elements is established by the functionals $\Lambda(x)$. For example, a point x is more efficient than y when $\Lambda(x) < \Lambda(y)$ or $\Lambda(x) > \Lambda(y)$. It can be shown that in the problems of determining effective points $x_0 \in X^*$ in the presence of constraints $x \in Q_1$, the functional $f = \lambda\Lambda'(x_0)$, where $\Lambda'(x_0)$ is the Frechette derivative at the point x_0, is a reference functional to Q_1, at the point x_0 (i.e., $(f, x_0) < (f, x)$ for all $x \in Q_1$.

Thus, the task of analyzing the results of observations in the monitoring process is reduced to determining the reference functionals in the observation points, which makes it possible to assess the deviation of the observed points from the effective ones.

In terms of functional analysis [4, 5]: let Q be a set in a linear topological space E, E' – conjugate space, $x_0 \in Q$ – outermost point of Q, K_b – cone of possible directions of Q in the point x_0, K_k – cone of tangent directions for Q in x_0. If the set of linear functionals reference to Q at the point x_0, is denoted by Q^*, then $Q^* = f \in E', f(x) \geq f(x_0)$ for all $x \in Q$, i.e., the reference functional and the boundary point make $x_0 \in Q$ it possible to distinguish the set Q. We can show that if Q is a closed convex set, then $Q^* = K_k^*$, i.e. it forms cones formed by the set of linear functionals, which are reference to Q at x_0. The cone of tangent directions can be defined by the Frechette derivatives of the operators (convex functions) which link the sets of parameters and performance measures.

Let us consider the methods of finding K^* for the ways of setting K with the help of different functionals.

Variant 1. For a cone of decreasing directions K_0. A functional $\Lambda(x)$ in linear space E has a derivative $\Lambda'(x_0,g)$ at a point x_0 in the direction g, i.e. there exists

$$\lim_{\varepsilon\to+0}\frac{\Lambda(x_0+\varepsilon g)-\Lambda(x_0)}{\varepsilon}=f(x_{0,}g). \qquad (22)$$

$\Lambda(x)$ satisfies the Lipschitz condition in the neighborhood x_0 (for some $\varepsilon_0>0$ will be $|\Lambda(x_1)-\Lambda(x_2)|\le\beta\|x_1-x_2\|$ at all $\|x_1-x_0\|\le\varepsilon_0$, $\|x_2-x_0\|\le\varepsilon_0$)) and $\Lambda'(x_0,g)<0$, then $\Lambda(x)$ – correctly decreasing at x_0, and $K=\{g:\Lambda'(x_0,g)<0\}$.

Variant 2. For a cone of possible directions. In the case of a set which is not defined by a functional. If Q is a convex set, then the set of decreasing directions K_b at a point x_0 has the form

$$K_b=\{\lambda(Q-x_0),\lambda>0\},$$

$$\text{(i.e. } K_b=\{g:g=\lambda(x-x_0),x\in Q,\lambda>0\}).$$

Variant 3. For a cone of possible directions. In the case of definition Q by means of affine sets: $E=E_1\times E_2$, E_1, E_2 are linear topological spaces, the set of efficiency features is defined in E_2, D is a linear operator from E_1 to E_2, $K=\{x\in E,\ x=(x_1,x_2):Dx_1=x_2\}$, $K^*=\{f\in E',\ f=(f_1,f_2):f_1=-D^*f_2\}$, and as a reference separating function we can use

$$f(x)=(-D^*f_2,x_1)+(f_2,x_2)=-(f_2,D^*x_1-x_2).$$

The application of this function to divide the sets in the parameter space and to formulate rules that establish a correspondence between the parameter sets and the values of performance indicators can provide identification of states in the LC REM monitoring process.

Variant 4. For a cone of tangent directions. $P(x)$ is an operator from E_1 to E_2, differentiable in the neighborhood of the point x_0, $P'(x)$ is continuous in the neighborhood of x_0, and $P'(x_0)$ maps E_1 to all E_2 (i.e. the linear equation $P'(x_0)g=b$ has a solution g for every $b\in E_2$), the set of tangent directions K to the set $Q=\{x:P(x)=0\}$ at a point x_0 is a subspace $K=\{g:P'(x_0)g=0\}$.

Variant 5. A typical case for a cone of tangent directions. Let $x\in R^m$, $Q=\{x:G_i(x)=0,\ i=1,...,n\}$, where $G_i(x)$ are functions continuously differentiable in the neighborhood of point x_0, $G_i(x_0)=0$, $i=1,...,n$, and vectors $G_i'(x_0)$ are linearly independent. Then $K=\left\{g\in R^n:\left(G_i'\left(x_0\right),g\right)=0,i=1,...,n\right\}$. Here $E_1=R^m$, $E_2=R^n$, $P\left(x\right)=\left(C_1\left(x\right),\dots,G_n\left(x\right)\right)$, $P'\left(x_0\right)$ is a matrix $m\times n$ with i-th column equals $G_i'\left(x_0\right)$.

Variant 6. In the process of monitoring, it is necessary to determine whether the effective value of the function REM characteristic $w\left(z\right)$, in the simplest case the extreme value of the differentiable target function of one variable is provided, for this purpose it is necessary to check whether the derivative is equal to zero at the observed value of the parameter. For multidimensional target functions and their arguments this problem can be considered within the framework of set theory and functional analysis.

The formalization in the problem of observing the optimal tuning, as one of the LC REM processes, is that it is necessary to evaluate the optimality of the tuning process function $v\left(z\right)\in M$ where z is a parameter that determines the numerical value of the required characteristic $w\left(z\right)$ of the tuning object to provide a phase trajectory that provides equality $w\left(0\right)=c$, $w\left(Z\right)=d$, and the extremal value of the integral functional $\int_0^Z \Phi\left(w\left(z\right),v\left(z\right),z\right)dz$, in the presence of the relation given by the differential equation $\frac{dw\left(z\right)}{dz}=\varphi\left(w\left(z\right),v\left(z\right),z\right)$.

In problems requiring the maximum correspondence of the optimized characteristic and some desired one, the criterion of minimum of the root-mean-square deviation finds application

$$W_2\left(X\right)=\overline{\left(Y\left(X\right)-Y^*\right)^2}, \qquad (23)$$

where Y^* – the desired or required by the technical specification value of the characteristic.

For a characteristic given by a discrete set of points, the target function

$$W_2\left(X\right)=\frac{1}{N}\sum_{i=1}^{N}\gamma_i\left(Y\left(X,p_i\right)-Y_i^*\right)^2, \qquad (24)$$

where N – the number of discretization points of the independent variable p;

$Y\left(X,p_i\right)$ – the number of discretization points of the independent variable;

γ_i – weight coefficient of the *i*-th value of the optimized characteristic, reflecting the importance of the *i*-th point in comparison with the others (as a rule, $0 < \gamma_i < 1$).

In some optimization problems it is necessary to ensure that the optimized characteristic exceeds or does not exceed some given level. These optimality criteria are realized by the following functions:

– to ensure that a given level is exceeded

$$W_3(X) = \begin{cases} 0 & \text{at} \quad Y(X) \geq Y_L^*, \\ \left(Y - Y(X)\right)^2 & \text{at} \quad Y(X) < Y_L^*; \end{cases} \tag{25}$$

– to ensure that the set level is not exceeded

$$W_4(X) = \begin{cases} 0 & \text{at} \quad Y(X) \leq Y_U^*, \\ \left(Y - Y(X)\right)^2 & \text{at} \quad Y(X) > Y_U^*, \end{cases} \tag{26}$$

where $Y_L{}^*$, $Y_U{}^*$ – lower and upper limits of the allowable area for the characteristic $Y(X)$.

If it is necessary that the optimized characteristic passes in some acceptable zone (corridor), use a combination of the previous two optimality criteria

$$W(X) = \begin{cases} 0 & \text{at} \quad Y_L^* \leq Y(X) \leq Y_U^*, \\ \left(Y(X) - Y_U^*\right)^2 & \text{at} \quad Y(X) > Y_U^*, \\ \left(Y_L - Y(X)\right)^2 & \text{at} \quad Y(X) < Y_L^*. \end{cases} \tag{27}$$

In cases where you want to realize only the shape of the curve, while ignoring the constant vertical displacement, the shift criterion is used

$$W_6(X) = \sum_{i=1}^{N} \gamma_i \left(Y_i^* - Y(X, p_i) - Y_{cp}\right)^2, \tag{28}$$

where $Y_{cp} = \frac{1}{N} \sum_{i=1}^{N} \left(Y_i^* - Y(X, p_i)\right)$.

Important characteristics of computational process and, first of all, the convergence of optimization process depend on the kind of target function. Signs of target function derivatives on controllable parameters do not remain constant in the whole admissible domain, the latter circumstance leads to their gully character (for example, circuit design problems), which leads to large computational costs and requires special attention to the choice of optimization method.

Another peculiarity of target functions is that they are usually multiextremal and along with the global minimum there are local minima.

Multicriteria optimization problems constitute a general class of problems of identification of the set of effective solutions. They are characterized by the fact that a binary relation on the set of alternatives, from which it is necessary to choose, is connected with a set of indices - criteria forming a vector efficiency criterion. This binary relation is generated in different ways. So, if

$$W(x)=\left(W^1(x),...,W^m(x)\right) \tag{29}$$

vector criterion on set X, then the binary relation can be a Pareto relation or a Slater relation. In other cases the binary relation on X is set by the system of DM preferences. It is assumed that the main source of information is a person who has sufficient information to make a (single) decision. Identification of the system of preferences of the DM is one of the main problems in solving multicriteria problems. Usually the procedures for identifying preferences of the DM are built on the language of vector evaluations of alternatives, i.e. based on the values of the vector criterion.

Decision-making by the LPR is facilitated by finding the Pareto set or Slater set by criterion (29), here methodological problems lose their acuteness to a large extent, since the notion of solving a multicriteria problem has already been clearly defined. There remain difficulties of computational character typical for extreme problems.

Methods for solving the problem of searching for effective (Pareto-optimal) and weakly effective (Slater-optimal) alternatives are being intensively developed [6–8], there are programs, program packages and software systems implemented on computers.

The algorithms based on scalarization – reduction to the parametric family of scalar optimization problems – are of great «clarity».

From convex analysis it follows that if $x_* \in P(X,W)$ is an effective point in a linear multicriteria problem (with linear criteria in polyhedron *X*), then there exists vector Λ

$$\lambda \in \Lambda = \left\{ \lambda \in E^m \,/\, \lambda_i > 0,\ i=1,\ ...,\ m;\ \sum_{i=1}^{m} \lambda_i = 1 \right\},$$

such that $x*$ is a solution to the linear and nonlinear programming problem

$$\sum_{i=1}^{m} \lambda_i W^i(x) \to \max_{x \in X}. \tag{30}$$

Inversely, for any $\lambda \in \Lambda$ solution of problem (30) is an effective point.

Hence, it follows that well-developed methods of linear and nonlinear programming can be used for the search of $P(X,W)$ and use the result as an effective set in the process of mapping the situation related to the location of the set of real values of the attribute parameters, relative to the set of their effective values in the implementation of LC REM monitoring.

Conclusion

Developed methods for solving problems of selecting informative attributes for monitoring ECA LC, by classifying the states of ECA and LC processes in the space of attributes, each of which has a certain significance, which allowed to find a comprehensive criterion and formalize the selection procedures.

Improved methods for identifying ECA states that interpret them as elements of conjugate linear spaces and setting the initial sets using linear and nonlinear functional, which makes it possible to formulate rules for separating the sets in the space of states and the rules that establish matches between the sets of parameters a nd values of performance indicators of ECA LC. The application of these rules makes it possible to construct algorithms for optimizing the ECA LC indicators.

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MULTIFLOWED SOFTWARE MOTION CONTROL TECHNOLOGY FOR A TWO-LINK MANIPULATOR WITH FOUR DEGREES OF FREEDOM

Novoselov S., Sychova O., Tesliuk S.

This paper describes a multiflowed software motion control technology for a two-link manipulator with four degrees of freedom. The proposed technology uses a set of independent timers that allow to realize independent control flows of program execution. This technology uses the developed database structure to store the control program structure, which is a set of instructions, conditional and unconditional transition operators, waiting commands with the possibility of connecting to the PLC I/O ports via Modbus protocol. A characteristic feature of the proposed technology of executing commands in the program is the concept of folders. Folders in this sense are a grouping of commands that constitute a certain cyclic sequence of actions for the manipulator. Folders are not a visual component, but the essence, uniting several commands, executed one after another, in a database. An angular manipulator motion control program using visual components has been developed. Testing of the developed program was carried out, which showed its performance and reliability of the execution of commands given by the operator.

Introduction

Software control systems of manipulator movement are designed to create programs to control the movement of manipulator links, remotely control the device and visualize the current state of the moving mechanisms. The main task of the software tool is to facilitate the process of creating control programs and increase productivity by visualizing the motion of mechanical moving parts of the manipulator [1–3].

When creating control programs, the characteristics of the specific type of manipulator for which they are created are taken into account. Three basic functions of data transformations are aimed at solving three standard configuration problems of manipulator kinematics with protection of their solutions from dangerous manipulator movements:

– conversion of the angular configuration of manipulator links to Cartesian coordinates of a selected point on the gripper axis;

– transformation of the manipulator target coordinates with the gripper target parameters into the angular configuration of the manipulator links at the target point;

– linear interpolation of motion in Cartesian coordinates of the target vector according to the specified values of angular configurations at the current and target points of the planned motion of the manipulator gripper.

The aim of the work is to create a software tool for motion control and simulation of angular manipulators using visual components.

Multiflowed software manipulator motion control

The control object is a training model of a manipulator. The manipulator contains two movable joints and can rotate around the vertical axis. The manipulator also has a gripper for gripping and moving parts within its working area.

There are three stepper motors at the heart of the design. Each stepper motor realizes a certain degree of freedom. The control module, based on the Arduino Mega controller, controls the motors.

The manipulator has end sensors, one for each degree of freedom. At the beginning of operation, the control system is initialized. This starts a test run of each stepper motor and monitors the wear of the corresponding end sensor. If all sensors are triggered, the device enters the mode of waiting for commands from the user.

A simplified functional diagram of the industrial robot is shown in Fig. 1. An industrial robot has a mechanical part (containing one or more manipulators) and a control system for this mechanical part. In addition, the robot may have sensing means (forming together an information-sensory system), whose signals are fed into the control system [4, 5].

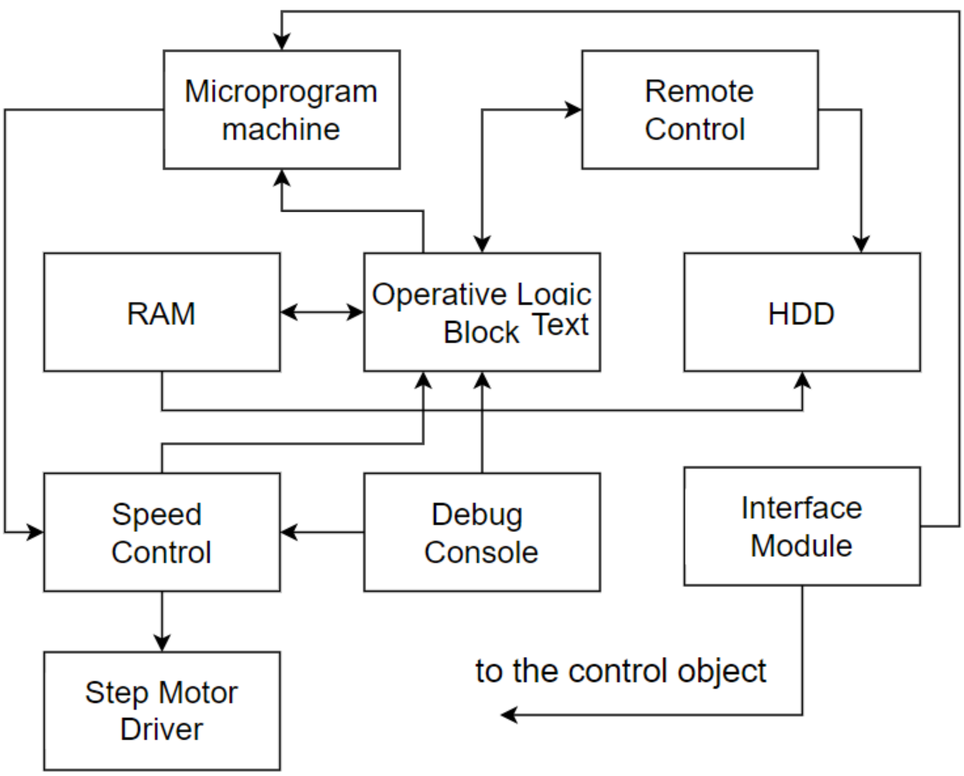

Fig. 1. Functional diagram of an industrial robot

As a rule, the executive mechanism of a manipulator is an open kinematic chain, the links of which are connected to each other in series by different types of joints. The combination and mutual arrangement of links and joints determine the number of degrees of freedom and the scope of the robot's manipulation system. It is usually assumed that the first three joints in the executive mechanism of the manipulator implement transport degrees of freedom (ensuring the presentation of the working body to a given location); the others implement orientation degrees of freedom (being responsible for the necessary orientation of the working device).

The structural diagram of the software is shown in Fig. 2.

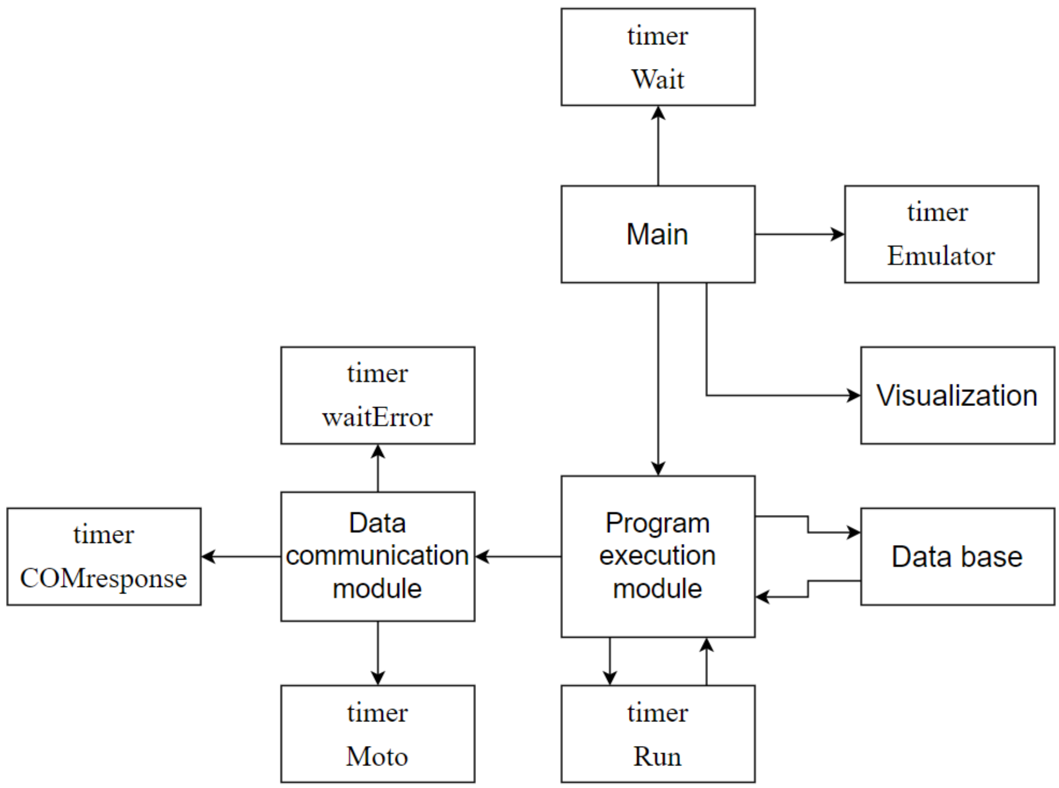

Fig. 2. The structural diagram of the software mean

The basic modules of the program are: the main module, the program execution module, the data communication module, the database module, and the visualization module.

There are also six timers in the program that allow to implement independent control flows of the program.

The program execution module organizes the operation of the instructions stored in the database. The appropriate module is engaged to retrieve the next command from the database. Each command is selected sequentially. The queue controls an independent flow, for which the timer_Run timer is responsible. When the next command is received, a command in G-Code format is prepared.

The following commands are involved in the program: positioning tool G0, turning on gripper M5, turning off gripper M3, turning on pump M1, turning off pump M2, turning off laser M6, turning off laser M7, turning on motor power M17, turning off motor power M18, manipulator calibration G28.

The visualization module is used in the program emulation mode to visually control the position of the manipulator links to facilitate setting the control program.

Each timer works independently. Synchronization is done with the corresponding states stored in the status_exec variable.

The operation of the program is organized using independent execution flows. Corresponding timers control each flow: timer_Moto, timer_Run, timer_Emulator, timer_Wait, timer_COMresponse, timer_waitError.

The timer_Moto is designed to cut off the power to the stepper motors if the manipulator is not used for a long time. The stepper motors used in the construction have no mechanical brakes. Therefore, they can lower the manipulator links to the bottom end position when the load turns off the power. In order to hold the cargo in the set position, the stepper motor drivers are provided with the function of switching on the holding current, which is 50% of the basic working current. This is done to prevent excessive heating of the motor windings.

However, some drivers do not have a hold current reduction function. In any case, to reduce the power consumption of the whole design it is appropriate to power down the motors if they are not used for a long time. By default, the timer_Moto interval in the program is set to 10s. This value is automatically updated with each command sent.

Fig. 3 shows a state conditions diagram explaining how to use the timer_Moto timer.

The main program flow calls the sendCommand function whenever an instruction needs to be sent to the manipulator control module. This function restarts the timer by setting a time interval of 10,000s.

When the wait time expires, it checks if there is communication with the serial data transmission port. If there is no communication, a message is displayed on the bar form status and the timer is turned off.

If there is communication, the corresponding G-Code is transmitted, which causes the power to the stepper motors to be turned off. The timer is then turned off and control is transferred to the main program flow.

The timer_Run timer is responsible for calling commands from the list that makes up the manipulator control program (Fig. 4).

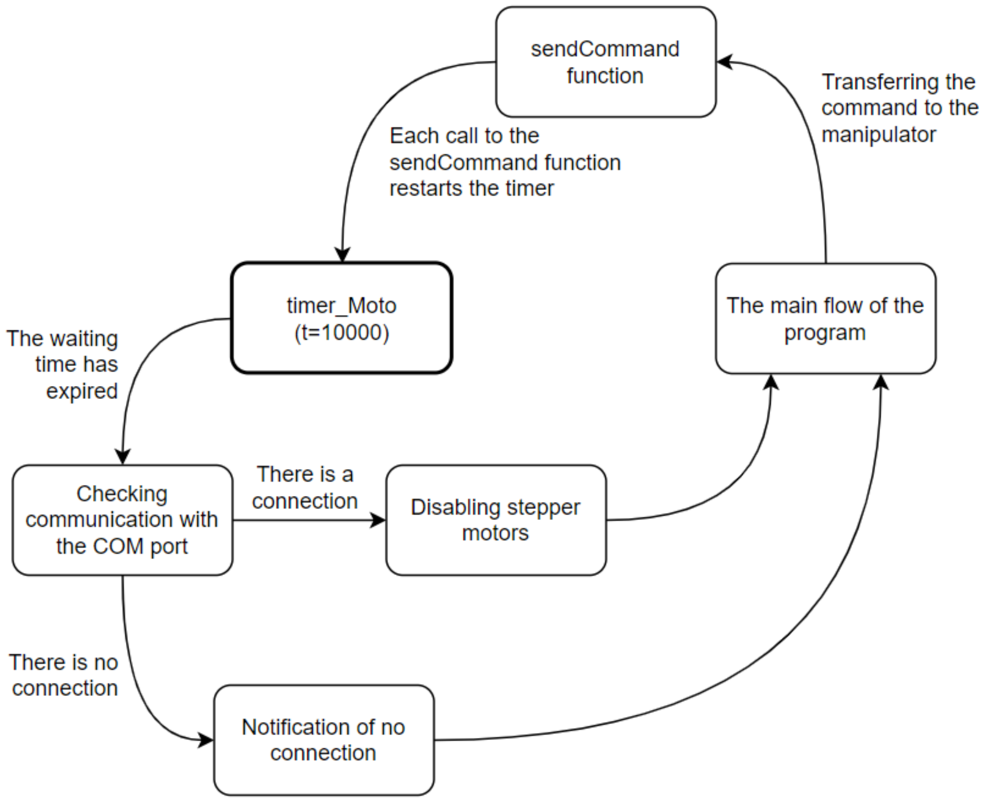

Fig. 3. Principle of timer_Moto usage

First, the current state of the status_exec variable is checked, which can have the following values:

– «OK» – the previous command is completed correctly, the application is in waiting state.

– «GET_OPERATION» – the program is in the state of searching for a new command.

– «EXEC_OPERATION» – the program is in the state of executing the current command.

– «STOP» – the program is in the state of completion.

A diagram of the state of the program execution process is shown in Figure 5.

A characteristic feature of the proposed method of executing commands in the program is the concept of folders. Folders in this case are a grouping of commands that make up a certain cyclic sequence of actions for the manipulator. Folders are not a visual component, but the essence, uniting several commands, executed one after another, in a database. Every program has at least one folder, which is the main folder. This structure is created at the beginning of the job and contains all the commands in the program.

Cycles can be used in the program. When a cycle is created, a new folder is also created in which all the commands that make up the body of the cycle will be placed. Folders can contain subfolders, which in turn can also contain folders. Entering a folder means that the sequential course of commands is interrupted and a new one becomes current - the cycle of commands entering the new folder.

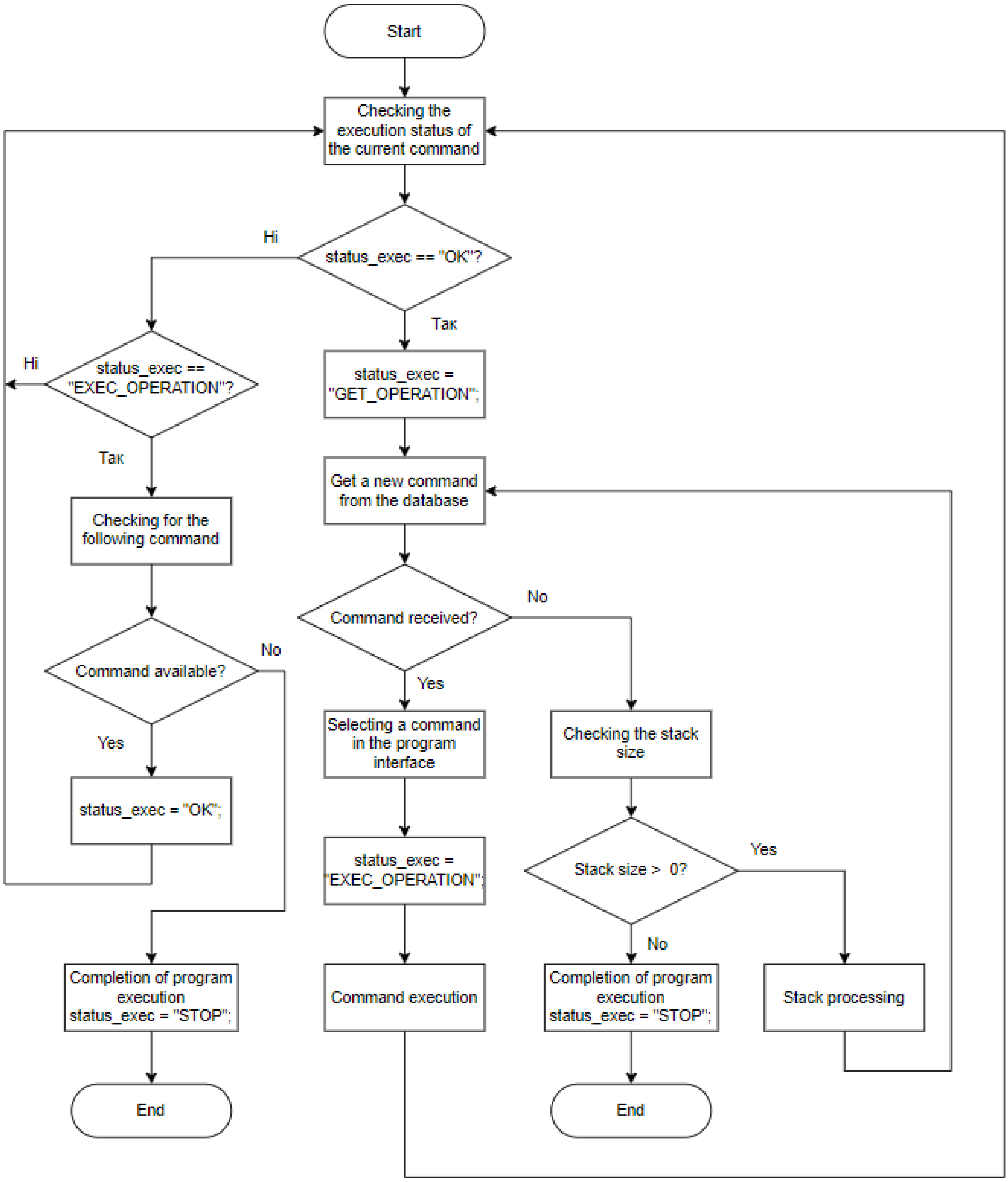

Fig. 4. Algorithm of the program pointer processing method

In order to be able to return to the previous command cycle, a stack is provided. The current program counter number is entered in the stack, and the ID of the command first in the new branch (the first command in the new folder) is passed to the counter. At the end of the cycle, the size of the stack is checked.

If it is greater than zero, the last entry, which is the return point to the previous cycle, is taken from it.

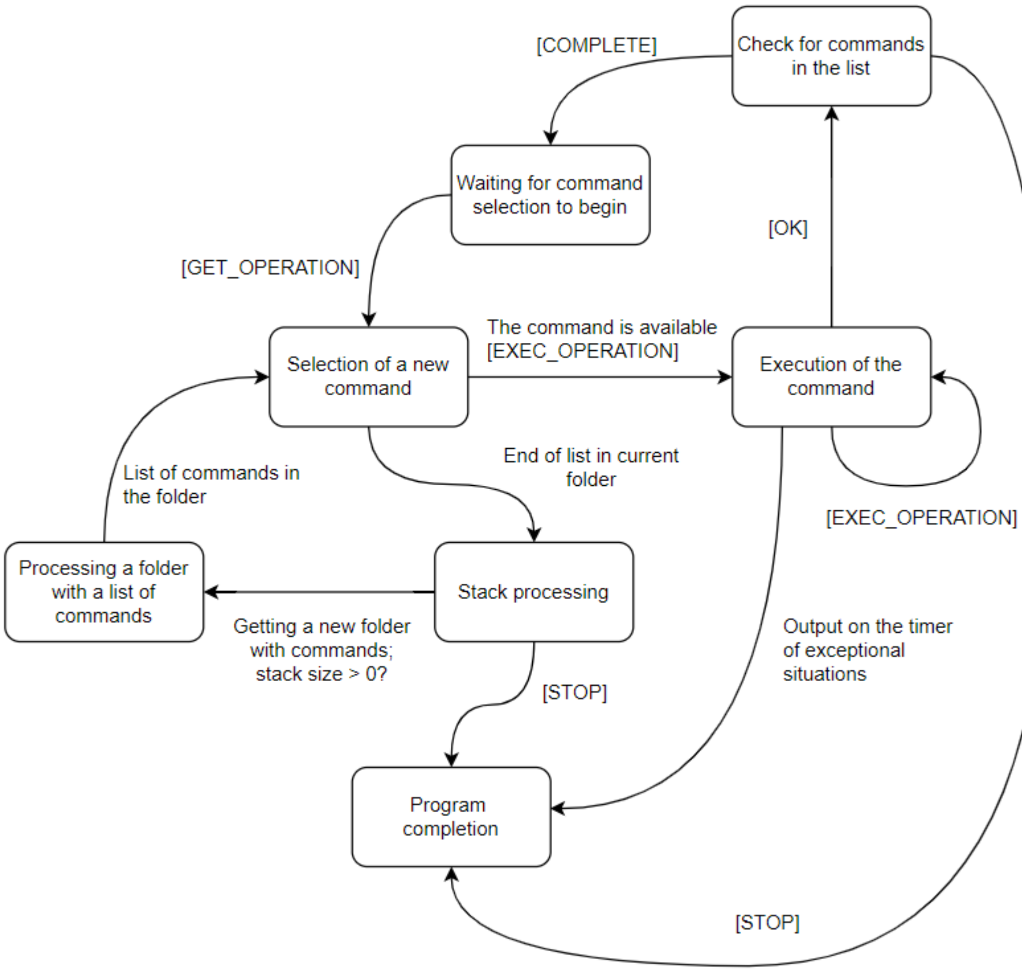

Fig. 5. State diagram for the program execution process

After getting the stack number, we call the search method in the database to find the identifier of the folder that contains the received command. After getting the folder number, a list of all commands in it is generated and a new value of the program counter is determined: cur_num_operation_exec++.

If the program counter number is out of the acceptable folder value range, the stack size is checked again. If it is equal to zero, the application is considered completed and the corresponding procedure with the value «status_exec = «STOP» is started.

If the stack size is not zero, the program execution continues according to the algorithm (Fig. 4) and the state diagram (Fig. 5).

The timer timer_Emulator runs only in emulation mode. Its purpose is to produce a delay of 500 ms on each command responsible for the movement of the manipulator links. This is done to visually assess the correctness of the commands and the sequence of the commands.

It should be noted that timer_Emulator does not run when the manipulator model is rendered on the computer screen. In this case, the sign of the completion of the manipulator link movement command is determined in real time if the virtual tool reaches a given point in space.

The timer timer_COMresponse is designed to organize the timing of the command execution by the manipulator control module. With the help of this timer after sending the Move command with the coordinates of movement of the working tool the current time of its execution is displayed. The timer stops after receiving a move confirmation from the control module in the form of one of the response options:

– «HOMING COMPLETE» – it is received when the calibration of the manipulator is completed.

– LINEAR MOVE» – accepted when the manipulator has finished moving to the set position.

– «OK» – accepted in case of completing the work of the manipulator's executive tool.

In all of the above cases, the current state of the curr_action variable changes to OK, which is an indication that the current state of the program is complete.

The timer timer_Wait is designed to delay the execution of instructions and the «Wait» command of the same name. When the timer_Wait command is executed, the argument of the current instruction is transmitted as a millisecond value. The PC screen displays the message «Program Execution Delay for XX ms». When the program delay is over, an acknowledgement curr_action=«OK» is generated.

The timer timer_waitError is used to generate an error message when the response from the manipulator control module is too long.

Development of a motion control program for an angular type manipulator using visual components

To implement the project of manipulator control and implementation of production equipment, it is necessary to present a functionally complete product that can work without connecting to the Internet. Therefore, to create a database, DBMS SQLite was chosen.

To store the project data, the table «Project» was developed. The project is created at the beginning of the work and to it are tied to all of the subsequent entities. One of the main entities is «Program». This entity is a description of the manipulator control program, specifying all operators and arguments transferred to them during the work.

The «SpecialPoint» table is used to store operational data about special points that are frequently used in a project. Such points can be the initial reference coordinate or the final coordinates of the working tool movement during the manipulator operation.

The SetupDevice table is needed to store the settings of the manipulator motion control program. Fig. 6 shows the database structure.

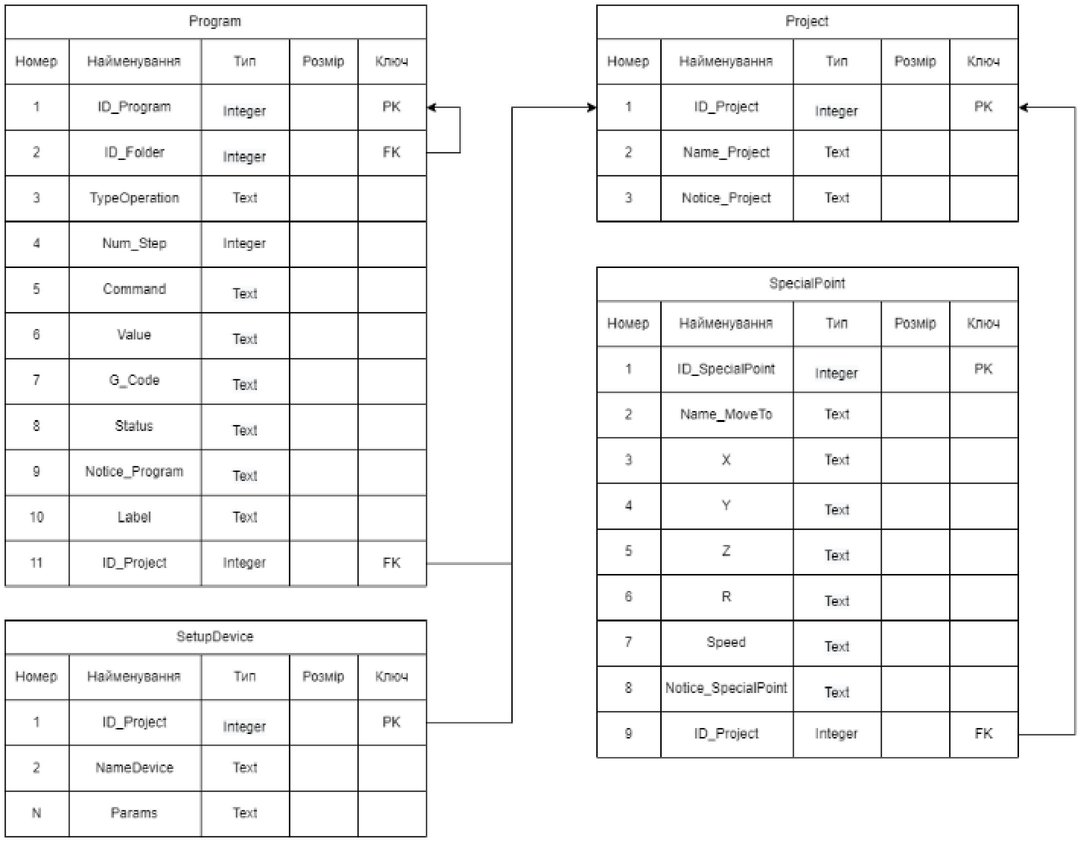

Fig. 6. Database structure

This figure shows the SetupDevice table in abbreviated form. The Params line shows that there are several fields in the structure to store the necessary parameters for the program to work. All tables are linked by the ID_Project field. When a new project is created, a new database file of the specified structure is created.

Fig. 7 shows the interface of the program. The left side of the interface is used to place commands to control the manipulator. A separate line that can be dragged and dropped within the program segment, thus changing the course of the program, represents each command. In the right side you can change parameters of each command. The contents of this area of the interface depend on the specific instruction. There are a total of six different types of instructions: Move To, While, Repeat, IF, GoTo, WaitInput.

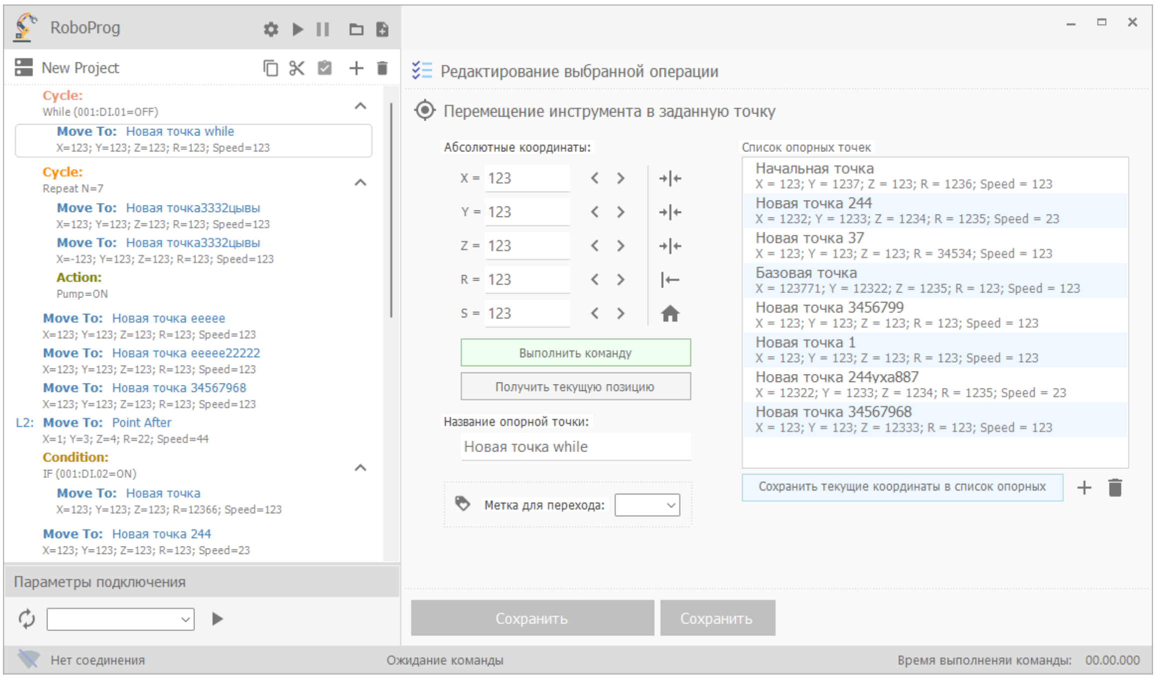

Fig. 7. The program interface and an example
of entering the «Move To» command parameters

The Move To command is used to move the manipulator tool to a given point in space. This command requires the following parameters: move *X* coordinate, move *Y* coordinate, move *Z* coordinate, move *R* coordinate, move *S* speed. The *XYZ* coordinate specifies the position of the tool's end point in 3D space. The *R* coordinate is the parameter that defines the displacement of the manipulator along the rail to which it is attached (if any).

The emulation mode provides a list of reference points. This list allows you to remember the key positions of the manipulator, often repeated during its operation. This list can be updated during the program operation. Points can be both added to and removed from the list. All of them are stored in the database table. Each point can be given a unique name to make it easy to identify during work.

Also in this mode it is possible to move the manipulator to a given point without executing the whole program. Thus, the operator has the opportunity to debug each step of the program during its creation in real time.

In order to read from the memory of the manipulator data about the current state of its links and automatically fill data fields with corresponding real coordinates a special button «Get current position» is provided.

The program also has a GoTo label. This parameter is used to assign a unique identifier to a command, which is used to unconditionally jump to it from any line in the program when using the GoTo statement.

The GoTo command allows you to jump from one command to another using a unique identifier that begins with the letter L. There are nine possible identifiers: L1...L9 respectively.

Using the command is simple enough: you must select the appropriate letter from the drop-down list. After that the instruction will be written in the command, for example, GoTo: Label=>L1.

The While command is one of two kinds of cycles. This cycle pauses the execution of the program until the specified condition is met. As a condition, it is implemented to wait for the set signal level to be set on the specified port of the industrial controller.

You can select digital or analog input type. In the first case you can select the input state either ON or OFF. If the input type is analog, you can set any value from –35565 to 35565. Also for the analog signal you can set the comparison signs «=», «>» and «<». In all cases you must specify the device address in modbus protocol format and the number of the digital or analog contact in the PLC.

The Repeat cycle type allows you to specify the number of repetitions for all the commands contained in the cycle body. All commands included in the cycle body are included in the virtual folder that joins them. Each command attached to a cycle can be moved by means of visual editing only within the given cycle. The command can be moved out of the cycle only by executing the «Cut» and «Paste» commands. All commands within a cycle are stored in the database with a reference to this cycle in the ID_Folder field.

The IF command is a conditional statement and is another representative of containers. This command decides whether a sequence of other commands included in the container body will be executed or if they will all be skipped. The conditional While command works directly with the PLC inputs. The ports are accessed via RS-485 network using modbus protocol or via Ethernet network using modbus TCP/IP. The condition of the IF command execution is the specified state of the discrete or analog inputs of the PLC.

The Wait command allows you to implement one of two delays: a time delay or a delay until a specified value is set on the specified PLC input.

When debugging a program to control a manipulator, animating the movement of its links and working tool from one point to another is very useful. Usually the task of 3D visualization requires the use of additional libraries and computing power. When developing the program it was decided not to use additional libraries, and to calculate the nodal points of the manipulator by means of C# in real time, using the laws of inverse kinematics.

To simulate the position of manipulator links and visualize their motion two views of the device are used: the top view and the side view (Fig. 8).

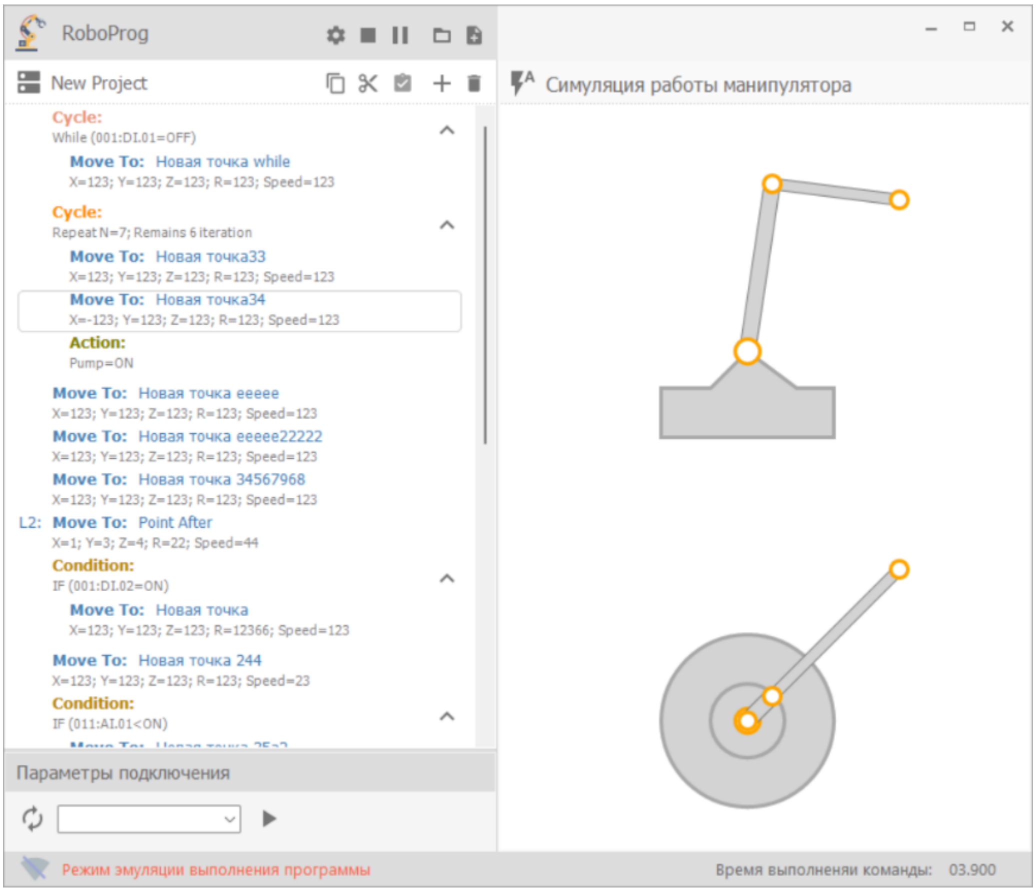

Fig. 8. Program interface in the manipulator simulation mode

These two views allow to estimate manipulator's motion without using isometric view of coordinate system. The difficulty in solving the problem is that the manipulator can rotate around the vertical axis, so the side view will be a transformed view of the vertical plane of vision.

Conclusion

This paper describes the developed technology of program control of robotic manipulator, describes the developed language of visual programming of industrial manipulator using multiflowed control of the processing of control commands. The proposed technology uses a set of independent timers, allowing to realize independent control flows of the program execution process. The process of task distribution between the flows and synchronization algorithm are described. The control object is a model of a robotic manipulator. The manipulator has two movable joints and can rotate around the vertical axis. In addition, the manipulator has a gripper for gripping and moving parts within its working area. The peculiarity of the developed method is that no additional libraries are used, and the calculation of the nodal points of the manipulator is performed by means of the selected programming language in real time using the law of inverse kinematics.

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STRUCTURAL AND PARAMETRICAL SYNTHESIS OF THE LAWS OF CRITICAL CONTROL

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Practical results related to the structural and parametric synthesis of critical control laws are presented. It is shown that when synthesizing digital controllers, it is most expedient to use discrete spaces that allow taking into account restrictions on the amplitudes of input signals. Approaches to the synthesis of critical controllers are considered. It is shown that the synthesis procedure is associated with minimizing the maximum absolute value of the generalized output for all possible values of input signals.

Introduction

In the practice of managing dynamic objects, one often has to deal with situations when the object does not belong to either statistical or stochastic ones, but is described by a set of target inequalities, that is, they are so-called critical [1].

For the synthesis of a critical control system, preliminary construction of both models of the control object itself and the environment is required. And if the object model can be described in terms of «Input – output», then the influence of the environment can be taken into account using a special description of the signals acting on the object [2–5].

The choice of one or another way of describing external signals is decisive in choosing a specific method for synthesizing the control law. At present, spaces $L(m,\delta)$ and $L(N,m_0,\delta_0)$ and are widely used, allowing to take into account restrictions on the amplitudes of input signals, and discrete spaces and, introducing restrictions on the space of the same signals.

General structure of the control law

Consider a discrete system $S_D(P,C)$ and a discrete space of inputs E . Let us set $\bar{w}=\left(y^*,w\right)$ and write down the ratio

$$v(\bar{w},C): k \to v(k,\bar{w},C),\, k \in N\,, \qquad (1)$$

which determines the relationship between the system output, external inputs and the structure of the control law C .

Then the efficiency of the functioning of such a system in the general case is determined by the criterion

$$J_E(C) = \sup\{|v(k,\bar{w},C)| : k \in N, \bar{w} \in E\}, \tag{2}$$

or, in the first approximation, the maximum absolute value of the generalized output for all possible inputs $\bar{w} \in E$ on the time interval $k \in N$.

In critical control systems, the main goal is to maintain a sufficiently low level of the output signal over the entire control interval, which can be expressed in the form of the inequality

$$J_E(C) \le \varepsilon_d \ , \tag{3}$$

where ε_d – is a positive value that determines the maximum possible value of $J_E(C)$.

At the same time, as noted above, the real control problem is described by a set of criteria specified in the form of a system of inequalities.

Consider the synthesis of a critical control law in the space of inputs $L(m_i, \delta_i)$, which ensures stable maintenance of the system of inequalities

$$J_L(C,\ m_i) \le \varepsilon_i,\ i = 0,1,2,\ldots,M\ , \tag{4}$$

where the number M specifies the number of all restrictions that must be maintained during the operation of the system. So, for example, if the input signal is $w(k) = 0.2(k+1)^{-1}\mathrm{sign}(\beta(k))$ for $k \le T_0$ and $w(k) = 0.1\cos k \times \mathrm{sign}(\alpha(k))$ for $k > T_0$, where $\alpha(k)$ and $\beta(k)$ – random variables with zero mathematical expectation, then the system of target inequalities can be specified in the form

$$\begin{cases} J_L(C,\infty) \le \varepsilon_1, \\ J_L(C,2) \le \varepsilon_2. \end{cases}$$

Note also that in a problem with one criterion $J_L(C,\infty) \le \varepsilon_1$ and inputs belonging to $L(\infty,1)$, the synthesis problem reduces to minimizing

$$\varepsilon_1 = \min_C \{J_L(C,\infty)\}$$

and is equivalent to an 1^1 optimization problem.

Let the control object be described by ARMAX, a model of the form

$$A(q)y(k) = q^{-d}B(q)u(k) + C(q)w(k), \tag{5}$$

where are polynomials $A \in R(q,n)$ with $a_0 = 1$, and $B \in R(q,m)$ and $C \in R(q,1)$ with $C_0 = 1$; $d \in N^+$; y, u and w are the generalized output, the control and external disturbing signals, respectively.

We also assume that the polynomials A and $q^{-d}B$ are coprime. Then the following equalities are true

$$AF + q^{-d}E = C\,, \tag{6}$$

$$AQ + q^{-d}BP = C\,, \tag{7}$$

where the polynomials $F \in R(q, d-1)$ with $f_0 = 1$, $E \in R(q, n-1)$, $Q \in R(q, d+m-1)$ with $q_0 = 1$, $P \in R(q, n-1)$, C are unique.

Using the parametrization introduced in [3], we can write the structure of the control law $C : y \to u$ in the form

$$C = (P + RA)\left(Q - Rq^{-d}B\right)^{-1},\ R \in A_1, \tag{8}$$

where P and Q are determined by equation (7).

Using (5) and (8), we can determine the relationship between the output signal $y(k)$ and the external disturbing signal $w(k)$ in the form

$$y(k) = \left(Q - \bar{R}q^{-d}B\right)w(k), \tag{9}$$

and also, to estimate the value of the optimization criterion

$$J_L(C,m) = \left\|Q - Rq^{-d}B\right\|_{A_n} \delta\,, \tag{10}$$

where $n^{-1} + m^{-1} = 1$.

Estimate (10) can be obtained from the following considerations. We introduce a polynomial

$$H = Q - Rq^{-d}B$$

and write the expression following from (9)

$$y(k) = \sum_{i=0}^{k} h_i w(k-i)\,. \tag{11}$$

Taking into account that $w \in L(m,\delta)$, and $n^{-1} + m^{-1} = 1$ and using Holder's inequality, we can write

$$J_L(C,m) \le \left\|Q - Rq^{-d}B\right\|_{A_n} \delta\,. \tag{12}$$

For each $k \in N^+$ there exists $w^* \in L(m,\delta)$, defined by the relation

$$w^*(k-i) = \begin{cases} \delta |h_i|^{n-1} \|H\|_{A_n}^{1-n} \operatorname{sign}(h_i), & if \quad 0 \le i \le k; \\ 0, \quad \text{otherwise}. \end{cases} \tag{13}$$

Substituting (13) into (11), we obtain

$$y^*(k) = \sum_{i=0}^{k} |h_i|^n \|H\|_{A_n}^{1-n} \delta$$

Since at $k \to \infty$

$$y(\infty) = \|H\|_{A_n} \delta,$$

then

$$J_L(C,m) \geq \left\| Q - Rq^{-d} B \right\|_{A_n} \delta. \quad (14)$$

Equation (10) follows from (12) and (14).

In the most general case, a polynomial under control actions can be represented as a product $B_1 B_2$, where the zeros B_1 lie outside the unit circle, and the zeros B_2 lie inside it. By setting $R = \bar{R}B_1$, we can introduce the ratio

$$Q - \bar{R}q^{-d} B = Q - Rq^{-d} B_2,$$

then, using (6) and (7), write down

$$Q = F + Dq^{-d},$$

where $D \in R(q, m-1)$.

So since

$$Q - \bar{R}q^{-d} B = F + (D - RB_2) q^{-d}$$

and

$$\left\| Q - \bar{R}q^{-d} B \right\|_{A_n} = \left(\|F\|_{A_n}^n + \|D - RB_2\|_{A_n}^n \right)^{1/n}, \quad (15)$$

it can be seen that the minimization problem $\left\| Q - \bar{R}q^{-d} B \right\|_{\bar{A}_n}$ can be reduced to minimization $\|D - RB_2\|_{\bar{A}_n}$, i.e.

$$\min_{\bar{R} \in A_1} \left\{ \left\| Q - \bar{R}q^{-d} B \right\|_{A_n} \right\} \leftrightarrow \min_{R \in A_1} \left\{ \|D - RB_2\|_{A_n} \right\}.$$

Thus, the characteristics of the control law are determined by the properties of the polynomial R, i.e. instead $J_L(C, m_i)$ of legal use $J_L(R, m_i)$. In this case, the problem of synthesizing the control law can be reformulated as follows: for given polynomials $D \in R(q, \bar{m}-1)$, $B_2 \in R(q, r)$ and $d \in N^+$ find a polynomial R that ensures the fulfillment of the system of inequalities

$$J_L(R, m_i) \leq \varepsilon_i, \; i = 0, 1, ..., M. \quad (16)$$

Denote by the R^0 polynomial $R \in A_1$ that ensures the fulfillment of (16). Then, as an admissible control law, one can use

$$C^0 = \left(PB_1 + R^0 A\right)\left(\left(Q - R^0 q^{-d} B_2\right) B_1\right)^{-1}, \qquad (17)$$

in this case, in the general case, there may exist a set $R \in A_1$ satisfying (16).

Synthesis of the optimal controller

Let us consider the problem of optimizing the parameters of the control law (regulator) (17) in the proposal of the minimum-phase object (5) and show that the optimal controller can be written as

$$C^0 = E\left(BF\right)^{-1}, \qquad (18)$$

while providing the minimum values of $J_L\left(C^0, m_i\right)$, i.e.

$$J_L\left(C^0, m_i\right) = \|F\|_{A_{n_i}} \ \delta_i, n_i^{-1} + m_i^{-1} = 1, \quad i = 1, 2, ..., M,$$

$$J_L\left(C^0, m_0\right) = \sum_{j=1}^{N} \|F\|_{A_{n_{0i}}} \ \delta_{0i}, \quad n_{0i}^{-1} + m_{0i}^{-1} = 1, \quad j = 1, 2, ..., N.$$

Due to the fact that the control object is the minimum phase, $B_1 = B$, and $B_2 = 1$. Then $R^0 = D$ provides a minimum $\| D - R \|_{A_{n_i}}$ because $\left\| D - R^0 \right\|_{A_{n_i}} = 0$.

Substituting R^0 into (17) and using (6) and (7), we can obtain the control law (18). Since, then $R^0 = D$ from (15) it follows that

$$\min_{R \in A_1} \left\{ \left\| Q - \bar{R} q^{-1} B \right\|_{A_{n_i}} \right\} = \left(\|F\|_{A_{n_i}}^{n_i} + \left\| D - R^0 B_2 \right\|_{A_{n_i}}^{ni} \right)^{1/n_i} = \|F\|_{A_{n_i}}, \quad i = 1, 2, ..., M.$$

Let us further consider a special but fairly common case of the input space $L(\infty, \delta)$. From (15) it follows that

$$\min_{R \in A_1} \left\{ \left\| Q - \bar{R} q^{-d} B \right\|_{A_1} \right\} = \|F\|_{A_1} + \min_{R \in A_1} \left\{ \|D - RB_2\|_{A_1} \right\},$$

those only the member $\|D\text{-}RB_2\|_{A_1}$ is subject to minimization.

Assume further that B_2 contains the only zero inside the unit circle $q^{-1}=\sigma(|\sigma|\le 1)$. Then there exists $R\in R(q,m-2)$ minimizing $\|D\text{-}RB_2\|_{A_1}$, i.e.,

$$\min_{R\in R(q,m-2)}\left\{\|D-RB_2\|_{A_1}\right\}=|D(\sigma)|, \tag{19}$$

the optimal value of which is determined by the expression

$$R^0=\left(D\left(q^{-1}\right)-D(\sigma)\right)\left(q^{-1}-\sigma\right)^{-1}. \tag{20}$$

Since, $\|D-RB_2\|_\infty \le \|D-RB_2\|_{A_1}$ for any $R\in A_1$ it is obvious that

$$\min_{R\in A_1}\left\{\|D-RB_2\|_\infty\right\}\le \min_{R\in A_1}\left\{\|D-RB_2\|_{A_1}\right\}.$$

It is known [3, 4] that the choice R^0 according to (20) ensures the minimum of the left-hand side in (19), while $D-R^0B_2$ it acquires the value $D(\sigma)$, while it is obvious that and $\|D-RB_2\|_\infty$ and $\|D\text{-}RB_2\|_{\bar{A}_1}$ are also equal to $D(\sigma)$.

Next, consider the situation when the polynomial $D\in R(q,m-1)$, and the coefficients of the unstable polynomial $B_2\in R(q,r)$ satisfy the condition

$$|b_r|\ge \sum_{i=0}^{r-1}|b_i|. \tag{21}$$

If $k=m-r$, then from the expression

$$H=D-RB_2$$

should

$$\begin{cases} h_m=b_r r_{m-r}; \\ h_{m-1}=d_{m-1}-b_r r_{m-r-1}-b_{r-1}-b_{r-1}r_{m-r}; \\ h_{m-2}=d_{m-2}-b_2 r_{m-r-2}-b_{r-1}r_{m-r-1}-b_{r-2}r_{m-2}. \end{cases} \tag{22}$$

Introducing the estimate

$$J_k=\sum_{i=0}^{r+k}|h_i|,$$

from (22) one can obtain the inequality

$$J_{m-r}\ge J_{m-r-1}+\left(|b_r|-\sum_{i=0}^{r-1}|b_i|\right)|r_{m-r}|,$$

from which, as a result of minimization, in turn, follows

$$\min_{R\in R(q,m-r)}\{J_{m-r}\}\ge \min_{R\in R(q,m-r-1)}\{J_{m-r-1}\}+\min_{r_{m-r}\in R}\left\{\left(|b_r|-\sum_{i=0}^{r-1}|b_i|\right)|r_{m-r}|\right\}. \tag{23}$$

Then from (21) and (23) it is obvious that $r_{m-r} = 0$, and

$$\min_{R\in R(q,m-r)}\{J_{m-r}\} \geq \min_{R\in R(q,m-r-1)}\{J_{m-r-1}\},$$

those the optimal value R belongs to $R(q,m-r-1)$.

Consider further the minimization problem $\|D-RB\|_{A_1}$ under the assumption that the polynomial B_2 has an arbitrary shape. Let us show that, in the general case, there are upper and lower bounds for the value of the minimum $\|D-RB_2\|_{A_1}$, i.e.,

$$\min_{R\in A_1}\{\|D-RB_2\|_\infty\} \leq \min_{R\in A_1}\{\|D-RB_2\|_{A_1}\} \leq \|D\|_{A_1}.$$

It follows from the definition that $\|\bullet\|_\infty$ and $\|\bullet\|_{A_1}$

$$\min_{R\in \bar{A}_1}\{\|D-RB_2\|_\infty\} \leq \min_{R\in \bar{A}_1}\{\|D-RB_2\|_{\bar{A}_1}\},$$

and since for $R=0$ we obtain the obvious inequality

$$D-RB_2 = D_1$$

then

$$\min_{R\in A_1}\{\|D-RB_2\|_{A_1}\} \leq \|D\|_{A_1}.$$

This circumstance allows us to use the H^∞-optimization procedure to obtain the lower bound $\|D-RB_2\|_{A_1}$. This bound can be very useful for assessing the possibility of ensuring the fulfillment of the inequality $J_L(R,\infty) \leq \varepsilon_1$.

Let us assume that $D \in R(q,m-1)$, and $B_2 \in R(q,r)$ has r different unstable roots. In this case, there is a finite $N_0 \in N^+$ such that

$$\min_{R\in A_1}\{\|D-RB_2\|_{A_1}\} = \min_{R\in R(q,N_0)}\{\|D-RB_2\|_{A_1}\}.$$

Considering the polynomial $H = D - RB_2$ and minimizing the $\|H\|_{A_1}$ norm, we can use the well-known result, which says that there is a finite $M_0 \in N^+$ such that the optimal polynomial satisfies the condition

$$H^0(\sigma_i) = D(\sigma_i),\ i = 1,2,...r,$$

where σ_i are zeros B_2, i.e., $B(\sigma_i) = 0$.

Since $H^0 - D$ the modulo is equal to $R^0 B_2$, then $R^0 \in R(q, M_0 - r)$. It can be seen that $R = R^0$ minimizes $\|D - RB_2\|_{A_1}$, while $N_0 = M_0 - r$.

Let us further consider a numerical method for finding the parameters of the synthesized controller that ensures the fulfillment of the system of inequalities (4).

Introducing the vector of coefficients of the polynomial $R \in A_1$ $r = (r_1, r_2, ...)^T$ and, replacing $J_L(R, m_i)$ by $J_L(r, m_i)$, we can rewrite the system of criteria (16) in the form

$$J_L(r, m_i) \le \varepsilon, \; i = 0,1,2,...,M. \tag{24}$$

Denoting through S_i the set of all vectors of coefficients (controller parameters) that ensure the fulfillment of the i-th inequality

$$S_i = \{r : J_L(r, m_i) \le \varepsilon_i\},$$

one can write the intersection of the sets

$$S = \bigcap_{i=0}^{M} s_i, \tag{25}$$

ensuring the fulfillment of the complete system (24).

To find the set (25), we will use the moving boundary method.

Let us first set $r \in R^j \left(j \in N^+ \right)$ and apply the method of moving boundaries to find the parameters of the control law. If the solution cannot be found for $r \in R^j$, then we assume $r \in R^{j+1}$ and repeat the search procedure again. The increase in order j continues until a solution is found that satisfies (24).

In some cases, the quality of the functioning of a critical system is determined mainly by only one of the criteria $J_L(r, m_i)$, $i = 0,1,2,\ldots,M$, which can be called the critical quality function. In this case, all other inequalities can be considered as constraints, which reduces the problem to the standard formulation adopted in optimization theory. To solve the problem, you can use both the considered method of moving boundaries and standard approaches adopted in non-linear programming.

We also note that although the standard methods 1^1-, H^2- and $H^\infty-$ optimization cannot be directly used to solve the problem of critical controller synthesis, they can be applied at the stage of preliminary estimation of the constraints that determine the structure and parameters of the system. So, if $\varepsilon_1 \le \inf\{J_L(r,1)\}$ or $\varepsilon_2 \le \inf\{J_L(r,2)\}$, with the help of these methods it is possible to evaluate whether such a controller exists at all. If the answer is negative, the problem should be reformulated already at the stage of formulation.

Synthesis of critical regulators

Let us consider the problem of synthesis of discrete critical algorithms in the spaces of inputs $D(m,\delta)$ or $D(N,m_0,\delta_0)$ according to the criterion

$$J_E(c)=\sup\left\{\left|v(k,\bar{w},c)\right|:k\in N,\bar{w}\in E\right\}, \tag{26}$$

associated with the maximum absolute value of the generalized output v for all input signals $\bar{w}$ in space E for all moments k of the control interval N [6]. In this case, as before, we will define the input space $D(m,\delta)$ as the set of all possible sequences w such that

$$\begin{cases} \sup\left\{\sum\limits_{i=k}^{k+m}\left|\Delta w(i)\right|:k\in N\le\delta\right\}, \\ \left|w(k)\right|<\infty \;\; \forall k\in N, \end{cases}$$

where $\delta\in(0,\infty)$, $m\in N^+$, $\Delta w(k)=w(k)-w(k-1)$, and the complex space $D(N,m_0,\delta_0)$ as the set of sequences w such that

$$w=\sum_{j=1}^{N}w^{(j)},$$

where $\left(w^{(1)},w^{(\pi)},...,w^{(N)}\right)\in D(m_{01},\delta_{01})\times D(m_{02},\delta_{02})\times...\times D(m_{0N},\delta_{0N})$.

In the general case, control algorithms related to criterion (26) are called critical ones [1], although there was no general approach to the synthesis of such procedures. A special case of critical control systems are critical regulators, in which there is no external setting signal.

Let us consider a system $S_D(P,C)$ in which there is no external setting signal y^*, i.e. the problem is reduced to stabilization of the output signal of the object in the vicinity of zero. In this case, the generalized output is replaced by the signal y, and the optimization criterion (26) takes the form

$$J_{DR}(C)=\sup\left\{\left|y(k,w,C)\right|:k\in N,w\in D\right\}, \tag{27}$$

where the symbol D denotes the input space $D(m,\delta)$ or $D(N,m_0,\delta_0)$.

The task of synthesis is to find the control law $C:y\to u$ that minimizes the objective function J_{DR}.

To simplify the calculations, we put $C(q)=1$ in ARMAX – models of the object included in the system $S_D(P,C)$, i.e.

$$A(q)y(k)=q^{-d}B(q)u(k)+w(k), \tag{28}$$

where is a polynomial $A(q)\in R[q,n]$ with, $a_0=1$, $B(q)\in R[q,m]$, pure delay time $d\in N^+$; y, u and w are the output, control, and disturbing signals, respectively.

Above, the validity of the identity

$$\Delta A(q)F(q)+q^{-d}E(q)=1, \tag{29}$$

in which the polynomials $F(q)\in R[q,d-1]$ with $f_0=1$ and $E(q)\in R[q,n]$ are unique.

Let us transform the description of the object (29) to the form of a d-step predictor, for which we multiply both parts of (29) by $\Delta F(q)q^d$

$$\Delta A(q)F(q)y(k+d)=\Delta F(q)B(q)u(k)+\Delta F(q)w(k+d), \tag{30}$$

after which, substituting identity (29) into (30), we obtain

$$\begin{cases} y(k+d)=\xi(k)+\Delta F(q)w(k+d), \\ \xi(k)=E(q)y(k)+\Delta F(q)B(q)u(k). \end{cases} \tag{31}$$

It follows from relations (31) that $y(k+d)$ it contains two terms: one of them is determined by known past control actions and measured outputs, and the other depends only on unchanging perturbations. Since the polynomial $F(q)$ has the order $d-1$, then all perturbations enter the description of the predictor with times greater than k, which in principle does not allow one to obtain estimates of the term from the measurement data $\Delta F(q)w(k+d)$.

Next, we return to the input space and consider the controller synthesis procedure for the case $0\le m<d-1$.

Set $|\Delta w(i)|=\gamma_i\delta$ for $i\in N$, where $\gamma_i\ge 0$. Then for $w\in D(m,\delta)$ the inequality

$$\sum_{i=k}^{k+m}\gamma_i\le 1 \quad \forall k\in N.$$

From (31) we further obtain the relations

$$|y(k+d)|\le|\xi_i|+\chi(\gamma_{k+1},\gamma_{k+2},...,\gamma_{k+d})\delta, \tag{32}$$

where

$$\chi(\gamma_{k+1},\gamma_{k+2},...,\gamma_{k+d})=\sum_{i=1}^{d-1}|f_i|\gamma_{k+d-i},$$

whence it follows that the synthesis problem can be reduced to finding a vector $(\gamma_{k+1},\gamma_{k+2},...,\gamma_{k+d})$ that maximizes the function χ or, what is the same, the objective linear function

$$\sum_{i=0}^{d-1}|f_i|\gamma_{k+d-i}$$

subject to restrictions

$$\gamma_{k+i}\geq 0,\quad i=1,2,...,d$$

and

$$\sum_{i=j}^{j+m}\gamma_i\leq 1,\ j=k+1,k+2,...,k+d-m\,.$$

As can be seen, the synthesis problem is reduced to a standard linear programming problem, which can be solved in a finite number of steps using the simplex method. As a result of the decision, the optimal vector $\left(\gamma_{k+1}^0,\gamma_{k+2}^0,...,\gamma_{k+d}^0\right)$ is obtained, leading to the value of the objective function

$$\max\left\{\chi\left(\gamma_{k+1},\gamma_{k+2},...,\gamma_{k+d}\right)\right\}=\sum_{i=0}^{d-1}|f_i|\gamma_{k+d-i}^0\,.$$

It is easy to see that the formulation of the linear programming problem does not change for all $k\in N$, so the optimal solutions $\left(\gamma_1^0,\gamma_2^0,...,\gamma_d^0\right)$ for all times k are the same.

Let us denote these solutions in the form $(\gamma_1^0,\gamma_2^0,...,\gamma_d^0)$, whence

$$\max\left\{\chi\left(\gamma_{k+1},\gamma_{k+2},...,\gamma_{k+d}\right):k\in N\right\}=\sum_{i=0}^{d-1}|f_i|\gamma_{d-i}^0\,.$$

Then we can rewrite (32) as

$$|y(k+d)|\leq|\xi(k)|+\sum_{i=0}^{d-1}|f_i|\gamma_{d-i}^0\delta\,,$$

leading to an assessment of the quality of regulation

$$J_{DR}(C)\leq\sup\left\{|\xi(k)|:k\in N\right\}+\sum_{i=0}^{d-1}|f_i|\gamma_{d-i}^0\delta\,. \tag{33}$$

A special case of perturbation for this situation is $w^*\in D(m,\delta)$, defined by the relation

$$w^*(k)=\begin{cases}0, & for\quad k\leq 0,\\ w^*(k-1)+\delta\gamma_k^0\,\mathrm{sign}\left(f_{d-k}\right), & for\quad 0<k\leq d,\\ w^*(k-1), & for\quad k>d\ .\end{cases}$$

Considering further the controller C_R in the form

$$\Delta F(q)B(q)u(k) = -E(q)y(k) \ , \tag{34}$$

one can see that $\xi(k) = 0$, and

$$y\left(d, w^*, C_R\right) = \sum_{i=0}^{d-1} |f_i| \gamma_{d-i}^0 \delta \,, \tag{35}$$

after which, using (33) and (35), we can conclude that the criterion value $J_{DR}(C)$ cannot be less than $y\left(d, w^*, C_R\right)$.

Thus, any controller that provides the value of the objective function

$$J_{DR}(C_R) = \sum_{i=0}^{d-1} |f_i| \gamma_{d-i}^0 \delta$$

and the value of the output signal

$$y(k, w, C_R) = \Delta F(q) w(k)$$

is critical.

In the particular case for $m = 0$, it is easy to see that the vector of optimal solutions $\left(\gamma_1^0, \gamma_2^0, ..., \gamma_d^0\right)$ is $(1,1,\ldots,1)$, and the target solution takes the form

$$\sum_{i=0}^{d-1} |f_i| \gamma_{d-i}^0$$

under restrictions

$$0 \le \gamma_i \le 1, \quad i = 1, 2, ..., d \ .$$

Obviously, the optimal value of the criterion for $m = 0$ is

$$J_{DR}(C_R) = \sum_{i=0}^{d-1} |f_i| \delta \ .$$

A more complicated situation arises in the case of $m \ge d - 1$. From (31) it follows that

$$\left|y((k+d)\right| \le \left|\xi(k)\right| + |f_0| \left|\Delta w(k+d)\right| + |f_1| \left|\Delta w(k+d-1)\right| + ...$$

$$+ |f_{d-1}| \left|\Delta w(k+1)\right| + \left\|F(q)\right\|_{A\infty} \sum_{i=k+1}^{k+d} \left|\Delta w(i)\right|,$$

or

$$y(k+d) \le \left|\xi(k)\right| + \left\|F(q)\right\|_{A\infty} \delta \ .$$

Taking into account (27), this inequality leads to an estimate of the control quality

$$J_{DR}(C) \le \sup\left\{\left|\xi(k)\right| : k \in N\right\} + \left\|F(q)\right\|_{A\infty} \delta \ .$$

For perturbations $w^* \in D(m,\delta)$ of the form

$$\Delta w^*(k) = \begin{cases} \delta \, sign(f_M), & if \quad k = M, \\ 0, & if \quad k \neq M, \end{cases}$$

where f_M – is the largest of the values $\{f_0, f_1, ..., f_{d-1}\}$, controller (34) leads to $\xi(k) = 0$ and the estimate

$$y\left(d, w^*, C_R\right) = \delta |f_M| = \|F(q)\|_{A\infty} \delta \ ,$$

those is also critical.

Thus, it can be argued that the critical controller C_R is invariant to the parameters m and δ the input space $D(m,\delta)$.

For the input space $D = D(N, m_0, \delta_0)$ and perturbations $w \in D(N, m_0, \delta_0)$, controller (34) is also critical. This can be shown by introducing the function

$$Q_R(k) = \begin{cases} \sum_{i=0}^{d-1} |f_i| \gamma_{d-i}^0, & 0 \leq k < d-1, \\ \|F(q)\|_{A\infty}, & k \geq d-1, \end{cases}$$

after which, carrying out transformations similar to the previous one, we obtain

$$J_{DR}(C_R) = \sum_{i=1}^{N} Q_R(m_{0i}) \delta_{0i} \ ,$$

$$y(k, w, C_R) = F(q) \sum_{i=1}^{N} \Delta w^{(i)}(k),$$

where the polynomial is defined by relation (29).

Thus, the introduced supremal controller ensures the quality of control

$$J_{DR}(C_R) = \begin{cases} Q_R(m)\delta, & for \quad D = D(m,\delta), \\ \sum_{i=1}^{N} Q_R(m_{0i}) \delta_{0i}, & for \quad D = D(N, m_0, \delta_0). \end{cases}$$

Conclusion

Practical results related to the structural and parametric synthesis of critical control laws in various metric spaces are presented. The general structure of the critical control law is proposed. Approaches to the synthesis of critical controllers are considered. A procedure for the synthesis of critical controllers based on multi-step optimal predictors has been introduced and justified. A procedure for calculating the parameters of an optimal controller based on the solution of a standard linear programming problem is proposed, and the optimality of the resulting solution is proved. The stability of a closed critical control system in the case of non-stationary external disturbances is analyzed. It is shown that after the end of the transient processes, the system «contracts» into a tube, the characteristics of which are determined both by the properties of the object itself (location of zeros and poles) and of the acting disturbances.

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PORTFOLIO MANAGEMENT FOR PUBLIC PARTICIPATION PROJECTS

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The relevance of the topic is due to the need for improvement and further development of methodological support of the portfolio management processes within the portfolio management introduction in the field of project management of local (territorial) self-government, including projects of public participation.

Introduction

The relevance of the topic is due to the need for improvement and further development of methodological support of the portfolio management processes under the circumstance of introduction of the portfolio oriented management in the field of by management projects of local (territorial) self-government, including projects of public participation (PP projects).

The purpose of the study is to improve and further develop the methodology support of the portfolio aligning process group under the conditions of PP projects performing regarding of the developing a concept for aligning of the PP projects portfolio.

The object of the study. Processes of aligning of PP projects sets for implementation.

The subject of the study. Methods and models for aligning of portfolio of projects.

The study's objectives are as follows: 1) to establish base of definitions for research and to identify project management knowledge areas relevant to the research subject; 2) to analyze, as interrelated, methodological approaches to: structuring categories; defining criteria for evaluation, selection and prioritization; optimization of PP project combinations as those presented in portfolios; 3) to formulate and test, using the database of the PP projects of Kyiv city, hypotheses relating to the significance of differences in the sets of the PP projects, separated by thematic directions, which determine the feasibility of presenting projects of thematic areas in the relevant subportfolios of the overall PP project portfolio; 4) to propose the model for optimization of the PP projects portfolio.

The methods of the study the method of scientific identification was applied while forming the base of definitions for the research; the method of comparative contrast analysis was applied in the analysis of methodological approaches to structuring, definition of criteria (evaluation, selection, prioritization) and optimization of the PP project portfolio; to test the hypotheses of significance of differences in the set of the PP projects, separated by thematic areas, the non-parametric criterion (test) of significance of Kruskal-Wallis was used; while building a model for optimization of the PP projects portfolio, the method of cost-benefit analysis, the time value of money concept, and an integer programming linear method were applied.

Literature review

As is well known, politics and projects are frequently viewed as the main ways of intervention into the economy at the state level and/or at the level of individual territorial communities.

Nearly all industrial markets and markets for specific goods (services) are impacted by macroeconomic policy means that determine the overall economic situation of the nation. These means should, in the first instance, be focused on preventing or resolving general crisis phenomena, stabilizing the economy, and promoting economic growth. When compared to the macroeconomic policy implemented in the nation, the means of economic policy that are implemented at the level of specific territorial communities within the parameters of the rights and obligations assigned to those communities can be seen as additional, or complementary, and as those that have an impact on all aspects of the activity of economic units that belong to these communities, as well as the working and recreational conditions of local residents.

It is important to understand that, when analyzing projects which implementation can be viewed as economic intervention at the level of the state as a whole or local territorial communities, policy tools and projects can act in some situations as interchangeable and in other cases as complementary forms of intervention. We can give the following issues as examples of policy instruments, carried out in the field of transport: taxation; subsidizing; direct (from the state or territorial communities) suppling of transport and related services; legislation and regulation; introducing restrictions on competition; consumer rights protection; pricing; licensing; purchasing (by the state or territorial communities) of transport services; moral influence; conducting research and creating conditions for development; provision of information; regulation of industries that generate input (resource) flows in relation to the transport sector. As we can see, potentially the means of policy have a greater impact in comparison with the expected results of separate projects. As a result, the introduction of new policies is prioritized over the execution of projects that are seen as alternatives.

At the same time, projects and instruments of policy can work together to solve a variety of issues. On the one hand, the policy establishes the necessary structural context, principally in terms of the legal, economic, and, more recently, environmental aspects; it also stimulates the desired responses of economic units and provides the necessary resources, among other things. On the other hand, the outcomes of the implemented projects can influence the formation of political decisions in different areas in the future.

Being aware that intervention in economic processes by the state is necessary due to the imperfection of the market economy, we have to note that it can lead to the desired outcome only when it is an «optimal» one. In the other case, i.e., when such intervention is excessive or insufficient, it fails to reach its goal.

Based on the aforementioned, it is vital to ask a number of questions before beginning to assess a particular project in detail. Why does not the market in this given situation perform its functions, why are we facing so called «market fiasco»? Is it an outcome of the market imperfection or intervention into economy, which happened to be not perfect? Do we have another way to solve the problem – more effective, efficient, harmonious and directly aimed at this problem – than the implementation of the project under consideration?

Depending on the respond to these questions all projects can be divided into two main groups: projects, aimed at overcoming market imperfection, and projects, which are supposed to correct the consequences of imperfect interventions in economy. The projects of the first group can, hypothetically, serve both as alternatives and supplementary to instruments of policy. It is worth mentioning, that regarding the projects of the second group it is desirable firstly to change policy in the corresponding areas, and then, in the conditions that have undergone the changes, we can consider the feasibility of implementation of the projects of this group.

At the same time, being a form of intervention into economy, at the level of individual territorial communities projects act as a mean of implementation of the development strategy for these territorial communities. This determines the need to direct them towards ensuring the achievement of relevant strategic goals. Aiming to involve local residents in various facets of community life through awareness and decision-making processes, realized in the form of drafting a project, to address local problems in distinct residential communities, districts, cities, etc., public participation projects (PP projects) are gaining increasing recognition in the territorial communities of Ukraine and the rest of the world. At the same time, based on the analysis of requests submitted for the implementation of PP projects, the latter can be divided, in terms of compliance with the established strategic objectives, at least into two groups. There are projects that clearly cannot be matched with specific strategic objectives, and may even contradict some of them, and projects that clearly meet strategic objectives, demonstrating the applicability of the existing strategy for the local community. Taking into account the significant number of requests for projects from the first group in certain areas, in the future, these areas can be identified as those that require the intervention of local governments through changes in the relevant components of policy and/or strategy.

Currently, we can observe high growth rates in the total number of PP projects and budgets allocated for their implementation. Particularly, in Kyiv, the budget for the PP projects that were approved for implementation climbed from 50 million hryvnias in 2017 to 170 million hryvnias in 2021, while the number of projects approved for implementation increased from 62 in 2017 to 348 in 2022. It is planned to allocate 200 million hrynvias for 393 projects in 2022. In order to address this, management must become more effective and efficient as for PP projects in general, as for their sets in the sphere of healthcare, education, transportation, and so on.

It is widely acknowledged that combining projects and programs into portfolios enables one to obtain a new management quality, increases the overall impact of their implementation, and gradually develops the portfolios themselves into an effective and efficient mechanism for implementing not only strategical goals but also their formation [1, 2]. The increasing importance of portfolio management in the theory and practice of project management is indirectly indicated by the fact that, since 2006, the largest professional organization in the field of project management, the Project Management Institute, PMI, singles out from its basic standard for project management – A Guide to the Project Management Body of Knowledge – develops and communicates to project management professionals a portfolio management standard. At the same time, until now, portfolios have been considered in scientific papers and portfolio management standards mainly in the context of the implementation of strategies by individual, mostly business, organizations or organizational networks.

Thus, the relevance of the scientific topic is due to the need for improvement and further development of methodological support portfolio management processes in the context of the introduction of portfolio-oriented management in the field of project management of local (territorial) self-government, including projects of public participation (equivalent to the term «public projects»).

The PMI has offered so far four versions of portfolio management standard, which were published in 2006 [3], 2008 [4], 2013 [5] and 2017 [6], respectively. Project management is one of those concepts that has many meanings, as was stated in the initial version of this standard. It was only ever affiliated with projects for a long time. However, today, it is becoming obvious that project management also deals with portfolio and program management, focusing on the thesis of «doing the right work», as opposed to the traditional project management and program management – «doing work right» [3].

In the Standard for Portfolio Management, the terms «portfolio» and «portfolio management» act as initial points of reference. Comparing the definitions of portfolio in different versions of the Standard for Portfolio Management of PMI, Table 1, we can come to a conclusion, that in the first three versions [3–5] a portfolio is considered as one, that includes projects, programs. and also other work, which is not included into previously mentioned components – projects and programs. At the same time, starting from the end of 2000, in the second edition of the Standard for Portfolio Management [4] and in some other standards of PMI the last one started to use the term «highest level portfolio», which, except for projects and programs, by definition may contain lower level portfolios. During the same time period, the professional community observes that in practice there is a tendency in any large portfolio to appear more or less stable groups of projects sporadically, and sometimes systematically. We can refer to these project groups as subunits (or subdivisions) of a single portfolio as long as they are just there to make management easier. However, when we start to allocate resources separately for a group and rank projects within such a group, we deal with singling out a portfolio of a relatively lower level within a portfolio of a relatively higher level. We can apply all the techniques and tools of traditional portfolio management to these new «units» [7]. These practices were taken into account to define a portfolio in the fourth edition of the PMI Standard for Portfolio Management through the introduction of subsidiary portfolios as portfolio components [6].

In the fourth version of the PMI Standard for Portfolio Management, developing the definition of the term «portfolio», PMI connects the existence of a portfolio to the adoption of specific strategies and the accomplishment of specific goals of the organization or business units [6]. At the same time, a portfolio assumes the existence of both current components and those that will be added in the future. It is obvious that the presence of multiple strategies and goals can result in a single organization having more than one portfolio. New project and program initiatives are included in existing or new portfolios. In addition, relatively bigger portfolios may include subsidiary portfolios. We may observe mainly hierarchical structuring. Portfolios can exist at different organizational levels, including the organization as a whole, a department, a business unit, or a function [6]. They can also be internal or external to the organization.

Table 1

Definition of Portfolio and Portfolio Management
in the versions of The Standard for Portfolio Management, published by PMI in the period from 2006 to 2017

Edition (version) of the PMI Standard for Portfolio Management	The definition of a portfolio	The definition of portfolio management
1	**2**	**3**
The first edition, 2006 [3]	A portfolio is a collection of projects (temporary endeavors undertaken to create a unique product, service, or result) and/or programs (a group of related projects managed in a coordinated way to obtain benefits and control not available from managing them individually) and other work that are grouped together to facilitate the effective management of that work to meet strategic objectives.	Portfolio management is the centralized management of one or more portfolios, which includes identifying, prioritizing, authorizing, managing, and controlling projects, programs, and other related work, to achieve specific strategic objectives. It is an approach to achieving strategic goals by selecting, prioritizing, assessing, and managing projects, programs and other related work based upon their alignment and contribution to the organization's strategies and objectives. Portfolio management combines (a) the organization's focus of ensuring that projects selected for investment meet the portfolio strategy with (b) the project management focus of delivering projects effectively and within their planned contribution to the portfolio.
The second edition, 2008 [4]	A portfolio is a collection of projects or programs and other work that are grouped together to facilitate effective management of that work to meet strategic business objectives.	Portfolio management is the coordinated management of portfolio components to achieve specific organizational objectives. Portfolio management is also an opportunity for a governing body to make decisions that control or influence the direction of a group of portfolio components (a subportfolio, program, projects, or other work) as they work to achieve specific outcomes. An organization uses the tools and techniques described in the standard for portfolio management to identify, select, prioritize, govern, monitor, and report the the contributions of the components to, and their relative alignment with, organizational objectives. Portfolio management is not connected with component management. Its aim is to ensure, that an organization is «doing the right job» rather than «doing the job right».

Table 1 continued

1	2	3
The third edition, 2013 [5]	A portfolio is a component collection of programs, projects, or operations managed as a group to achieve strategic objectives.	Portfolio management is the coordinated management of one or more portfolios to achieve organizational strategies and objectives. It includes interrelated organizational processes by which an organization evaluates, selects, prioritizes, and allocates its limited internal resources to best accomplish organizational strategies consistent with its vision, mission, and values. Portfolio management produces valuable information to support or alter organizational strategies and investment decisions. Portfolio management provides an opportunity for a governing body to make decisions that control or influence the direction of a group of portfolio components as they work to achieve specific outcomes. An organization uses the processes, tools, and techniques described in the standard to identify, select, prioritize, govern, allocate resources, monitor, and report the contributions of the portfolio components to, and their relative alignment with, organizational objectives. Portfolio management balances conflicting demands between programs and projects, allocates resources based on organizational priorities and capacity, and manages so as to achieve the benefits identified.
The fourth edition, 2017 [6]	A portfolio is a collection of programs, projects, subsidiary portfolios, and operations managed as a group to achieve strategic objectives.	Portfolio management is the centralized management of one or more portfolios to achieve strategic objectives. It is the application of portfolio management principles to align the portfolio and its components with the organizational strategy. Portfolio management can also be viewed as a dynamic activity through which an organization invests its resources to achieve its strategic objectives by identifying, categorizing, monitoring, evaluating, integrating, selecting, prioritizing, optimizing, balancing, authorizing, transitioning, controlling, and terminating portfolio components.

The modern sources of information in our opinion carries out a certain ambiguity of using the terms: «portfolio», «portfolio management», and others related terms. It's interesting to differentiate between the following two primary interpretations of «portfolio» in the context of this research.

In its first meaning a portfolio is put on a par with a project and a program, in the sense of temporary, i.e., such that has a limited duration in time, activity (actions, a set of activities, etc.). To a certain degree it seems that portfolio is considered, least partially, this way, for example, in the system model, which was proposed in the research paper [8]. One of the reasons to reach such a conclusion is the of life cycle phases, presented in the model as management objects for both projects and programs, as well as for portfolios. The same applies to the management processes [8].

We can note the use of the term «portfolio» as a time-limited activity in particular in resources on financial management, partly in project analysis, managerial accounting, etc. The research works of this direction deal with the issue of the conditions for project interaction – their components in portfolios – independent projects or dependent, i.e. substitutive or complementary by benefits and/or expenditures; peculiarities of application of NPV, payback period, IRR and other methods to access project efficiency not by separate projects but as a set of the specified project-components. We can see this interpretation of the term «portfolio» in certain context also in some versions of the PMI standard for portfolio management [3–6]. Therefore, in accordance with this first interpretation a portfolio is a certain totality (set) of components, in the capacity of which particular projects and programs are considered, and portfolio in this interpretation lasts for a limited period of time.

The second interpretation of the term «portfolio», which is separately dealt with in the Tab. 1, which we can see widely used in the contemporary theory and practise of project management, in regard to portfolio management, is connected with the interpretation of portfolio management as a regular, i.e. continuous, or operational activity. According to this interpretation, the phases of the portfolio's life cycle were either not singled out at all in the first three editions of the PMI portfolio management standard – or, according to the fourth edition [6], they were singled out in a different way than the phases of the project's life cycle. In other words, a portfolio serves within an organization as a permanent «shell» for projects and programs in a certain area. As it is highlighted in the work [7], an organization is able to operate with several portfolios at once in compliance with the PMI portfolio management standard. Although projects and/or programs within a portfolio may last only during a certain period of time, but the portfolio itself continues to function as an operational «shell» for projects and programs of a certain type.

In work [7], it was noted that, in contrast to the project life cycle, the portfolio life cycle is by its very nature cyclical, that is, repeated. For instance, this was brought up when the authors of this work assessed the first two versions of the PMI portfolio management standard. However, there is disagreement over whether it is generally reasonable to single out the various phases of the portfolio's life cycle or what content should have each phase. Some researches advocate such «reason ability», for example, mentioned above [7], while others share the view point of the first of the PMI portfolio management standard, in accordance with which a portfolio should be considered as a typical operational activity which includes a set of continuously performed processes. It means that the general process of portfolio management does not end. The only exceptions could be the cases when an organization refuses to employ portfolio-oriented management practice in general or an organization ceases to exist altogether. Simultaneously, in the first three versions of the PMI portfolio management standard the term «portfolio management process cycle» was developed [3–6]. But in the fourth version of the PMI portfolio management standard the term «portfolio life cycle» was introduced with description of content for each and their interaction.

The portfolio life cycle is considered as the ongoing processes and functions that occur to a set of portfolios, programs, projects, and operations within a continuous time frame [6].

Of course, it is hard to imagine a portfolio in which all process of its management will be performed evenly through the year, as it was noted in the research [7]. We can predict a correlation between a portfolio and cyclic activity of an organization. This cyclic activity can differ for various organizations and types of portfolio (a year, a quarter, a month, a week). However, certain portfolio management processes will be more typical for certain time periods, while others will be for others. As we saw above, the same opinion is fully presented in the fourth version of the PMI portfolio management standard [6]. This version reflected the above-mentioned preliminary considerations of the professional community regarding the interpretation of the life cycle of a portfolio, including those presented in the research [7]. This version specifically mentions that a portfolio has a life cycle, just like programs and projects do. A portfolio lasts comparatively longer than programs and projects, which are by definition marked by a limited duration in time. When a portfolio is no longer necessary due to the fact that portfolio goals have been met, or because some of its components have been halted or transferred to another portfolio, we can observe a portfolio being closed down. Portfolios can be united or divided to bring the benefits to the maximum [6].

In accordance with the fourth version of the PMI standard for portfolio management [6] a continuous portfolio life cycle includes: initiation, planning, execution, and optimization. Just as a portfolio evolves through its life cycle, so do information and decisions move between these phases. Although continuous, it need not always be sequential. For instance, a portfolio might go through a number of iterations of the planning phase and then move to execution at short notice. All phases, including initiation, are adaptive, flexible, and variable.

In our research, we use the definition of a portfolio and portfolio management in correspondence with their meanings provided in the fourth edition of the PMI Standard for Portfolio Management, Table 1, unless otherwise specified.

The current study focuses on the comparison and contrast of portfolio management processes vision, particularly the aligning process group, in accordance with various versions of the PMI Standard for Portfolio Management [3–6]. The aligning process group was singled out in the first version of the PMI Standard for Portfolio Management [3]. According to this version, the processes of this group are mostly realized by the organization during the period of review of its strategic goals, plans, and budgets, as a rule, at the end of a fiscal year. Some organizations have a shorter planning cycle. Furthermore, the necessity of these processes also arises when we observe sharp changes for conducting business [7]. The following processes were included in this group: identification of components; categorization of components; evaluation of components; selection of components; prioritization of components (determining the degree of priority, sometimes the term «rating» is used); balancing portfolio, and authorization (approval) of portfolio components [3].

In the second version of the PMI Standard for Portfolio Management the aligning process group retains its previous name and cited-above list of processes. At the same time, it is mentioned that the basis of these processes is formed by such portfolio management knowledge area as the portfolio governance. Meanwhile, the following processes: identification portfolio risks, analysis portfolio risks, and development portfolio risk responses were added to the cited-above list of processes. The basis of these new processes is formed by such portfolio management knowledge area as the portfolio risk management [4]. Also communication portfolio adjustment process was added. The knowledge area for this process is the portfolio governance.

In the third version of the PMI Standard for Portfolio Management the aligning process group is presented as one, which includes processes aimed at management and optimization of a portfolio. This group determines how portfolio components will be categorized, evaluated, selected for inclusion, modification, or elimination, and managed in the portfolio [5]. Within this group the following processes are pointed: manage strategic change, the basic of which is such portfolio management knowledge area as portfolio strategic management; optimize the portfolio – the portfolio governance management knowledge area; manage supply and demand – the portfolio performance management knowledge area; manage portfolio value – the portfolio performance management knowledge area; manage portfolio information – the portfolio communication management knowledge area; manage portfolio risks – the portfolio risk management knowledge area [5]. It is important to note that the defining process group, was introduced in the third version of the PMI Standard for Portfolio Management. It is a relatively new process group in the third version compared to the previous two versions of the PMI Standard for Portfolio Management. This group, as we can see, has partially overtaken some processes, which were considered as a part of the aligning process group in the previous versions of the PMI Standard for Portfolio Management. At the same time, if we link the groups of processes with portfolio management knowledge areas, we can notice that «traditional», as for the first, as for the second versions of the PMI Standard for Portfolio Management [3, 4], processes of aligning process group are studied within the portfolio governance management knowledge area. In particular, it is applicable to identification, categorization, evaluation, selection, prioritization, and balancing (hereinafter, optimization).

In the fourth version of the PMI Standard for Portfolio Management portfolio management processes act as those which are grouped according to the stage of the portfolio life cycle, identified in this version – as stages of the portfolio management process – initiation, planning, implementation, and optimization, as well as monitoring and control, if it is envisaged to separate this stage of the management process, which is not considered as a separate stage of the portfolio life cycle [6]. The processes of aligning process group, in the interpretation of the first three versions of the PMI Standard for Portfolio Management [3–5], and, in part, the processes of defining process group, which were introduced in the third version [5], mainly correspond to the process of initiation and planning group [6]. It is worth noticing that optimization (previously called balancing) as it is interpreted in the first three cited-above versions [3–5], occurs according to the fourth version not only at the optimization stage, but also to a large extent at the planning stage, in particular, at its beginning, and is also possible at the stage of implementation [6].

It is obvious that if we try to apply portfolio-oriented management methodology to the project management of local (territorial) self-government, including PP projects, we need in certain adaptation. In our work we do not set an aim to substantiate the necessity to single out certain processes, which may make up a group of processes for the aligning of a PP project portfolio, and accordingly, to define the content of these processes as the main actions that are supposed to be taken, as well as input and output data for each process in correlation with portfolio life-cycle stages as the stages of the portfolio management process. At the same time, for any structuring of portfolio aligning process group, it is of interest to investigate the problem of elaborating the methodological approaches considered in the relationship to: structuring – as separating of categories; definition of criteria for evaluation, selection, and prioritization; optimization of PP project sets – such as those presented in portfolios. At the same time, the research gap is identified as the absence of methodological support for the development of the above-mentioned approaches.

Concept for aligning of the PP projects portfolio

In general, the process of evaluation and selection of PP projects for implementation is as follows. Requests for PP projects must undergo a preliminary selection procedure at the relevant executive structures of the territorial community. Then, those of the requests that have successfully passed the preliminary selection are offered for consideration to the residents of the territorial community. Each resident, as a votes, receives a specific predetermined amount of votes. The definition of «a resident of the territorial community» may differ.

Additionally, projects are evaluated, selected, prioritized, and optimized in accordance with preset criteria depending on the amount of votes obtained as a distinct indicator or in a predetermined combination with other indicators. The group of projects created in this manner is then transferred for implementation.

The generalized vision of the concept for aligning of the PP project portfolio offered by the authors is presented in Figure 1.

Let us consider in detail the interrelated approaches to the PP portfolio aligning. These approaches were identified in the above concept, Figure 1.

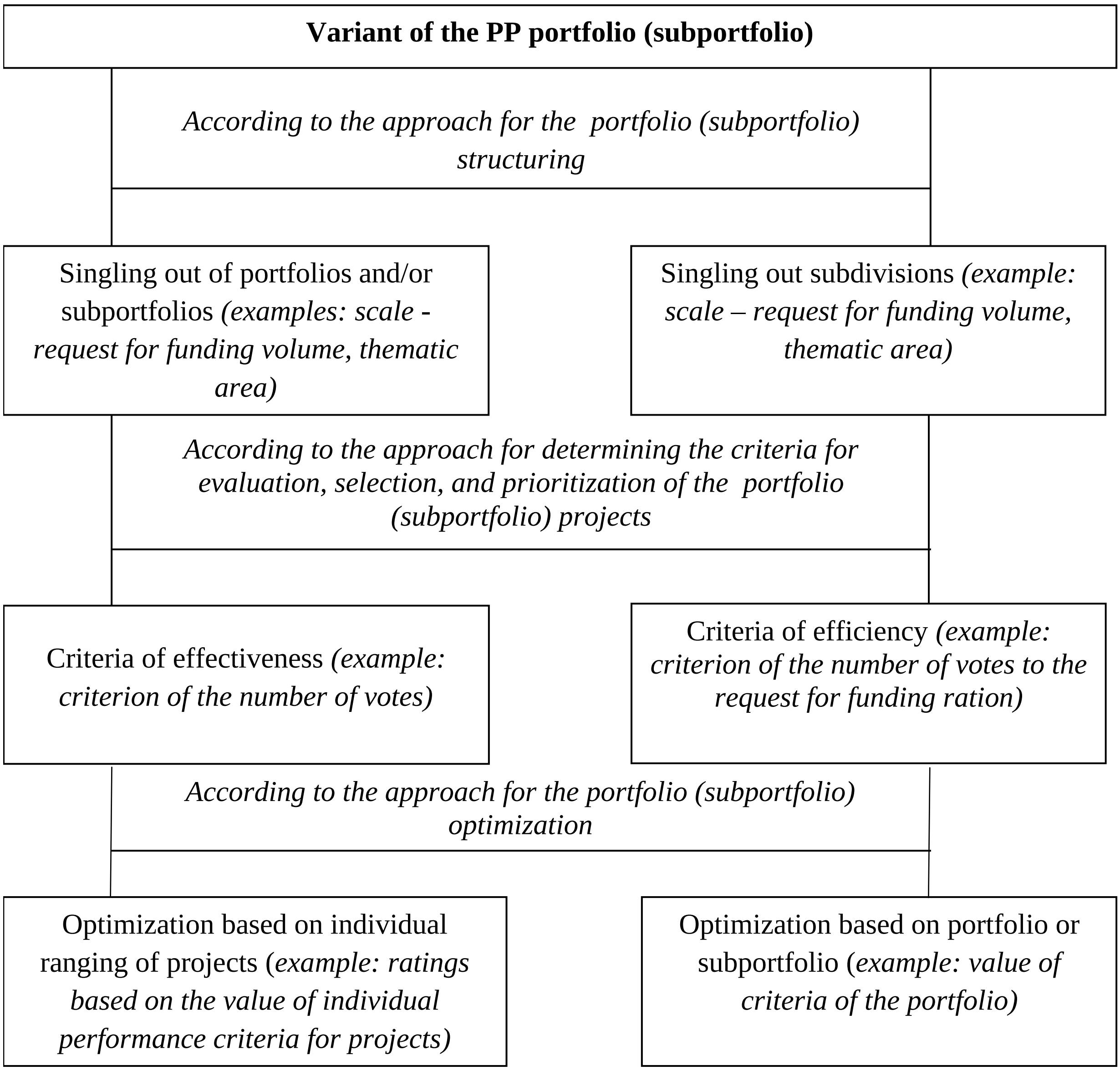

Fig .1. The concept for aligning of the PP projects portfolio

The analysis of existing practices regarding to the aligning processes of a set of the PP projects for implementation, which is considered in this paper as a portfolio, gives us grounds to distinguish at least two different approaches for structuring this portfolio. The first approach does not provide for a separate preliminary allocation (fixation) of budget regarding any component of the PP portfolio. Projects that differ in the parameters that these projects characterize, for example, by thematic focus, request for funding volume, etc., receive their rating within the general list, according to which they can later be prioritized within the thematic list, and a joint budget is allocated to them. Accordingly, following the interpretation of the portfolio or subportfolio provided in the review, we can only deal with the subdivisions of the portfolio, which are singled out in most cases only for ease of management. We can provide as example public projects in Kyiv, according to which it is proposed to single out the following ten thematic areas for implementation in 2022: roads, transport; ecology; housing (utilities, energy efficiency); health; information technology (IT); culture, tourism; youth, sports; education, civil society; social security, inclusion; interthematic, innovation. In particular, for each project, the city working group on public budget, if the localization of the project is citywide, or district working group on public budget, in the case of district localization of the project, appoints a person responsible for project appraisal. There are other aspects of PP projects management in Kyiv, the conditions for which depend on the thematic direction of the PP project [9]. At the same time, allocation of separate budgets for each thematic area is currently not provided for.

According to the second cited-above approach for structuring the PP projects portfolio, in contrast to the first, a separate rating and budgeting of projects that differ significantly in the values of certain defined and selected for categorization parameters are provided. If we deal with public projects in Kyiv for 2022, two categories are singled out: small and large projects, as it was in previous years. The group of small PP projects accepted for implementation in Kyiv in 2022 includes projects with a budget (expenditure) of 100 000 to 999 900 hryvnias, and the group of large projects includes those with a budget of 1 000 000 to 3 000 000 hryvnias [9].

Thus, now, in the «language» of portfolio-oriented management, we can interpret the set of PP projects in Kyiv for 2022 as a portfolio, which includes two categories: the category of small and the category of large projects as its subportfolios. As it was mentioned above, we can deal with the subdivisions of the PP project portfolio or subportfolio, for example, in the case of Kyiv, in accordance with thematic areas.

As criteria for evaluation, selection, and prioritization of projects for implementation mostly two criteria are used as alternatives. These are the criterion «number of votes» received by the PP project for support (hereinafter – the criterion of the number of votes) and the criterion of the ratio of the number of votes received by the project for support to the request for funding volume for the PP project (hereinafter-the criterion of the ratio of the number of votes to the request for funding). Carrying out a comparative and contrast analysis of the two outlined approaches for determing the criteria for evaluation, selection, and prioritization of the PP projects portfolio, we can point out that an advantage of the first approach is that, first of all, it «equalizes» in the community's vision all projects in their quest to be implemented at the expense of the PP budget (the term «public budget» is used as a synonymic term). This, to the greatest extent, corresponds to the essence of the development of the «movement» of PP projects as such. At the same time, this apparent «equality» can end up being a myth. This is partly because initiatives that match specific criteria are occasionally, a priori, comparatively more likely to receive more votes. Nevertheless, they may not necessarily have higher social or financial performance when viewed objectively. For example, this is observed for relatively significantly larger projects than others in the relevant list, which is reflected in the request for funding. If we stick with the previous example, large projects tend to «lose» when a different criterion for evaluation, selection, and prioritization of projects for implementation is chosen – the ratio of the number of votes to the request for funding. It is important to keep in mind that by selecting this criterion, which enables us to consider efficiency, we have, in some ways, violated in the eyes of citizens who participate in these projects the concept of «equality», in one way or another – which is based on the number of votes received – real or imagined – by PP project.

When we are going to optimize the PP projects portfolio (subportfolio) we have at least two ways for formulating of tasks for the optimization. We are to decide whether the optimization will be applied exclusively based on individual ranking, gained by project according to chosen criteria as a result of voting, or wheather the optimization will concern portfolio (subportfolio) as a whole, Figure 1.

Structuring of the pp projects portfolio

Research questions

Within the given research, we have carried out an investigation, the main questions of which sounded the following way.

Q 1: Do the requests for funding volume of public projects submitted in 2019 and those waiting for implementation in 2020 in Kyiv differ significantly in regards to singled out thematic areas in the singled out categories (subportfolio) of small projects?

Q 2: Do the requests for funding volume of public projects submitted in 2019 and those waiting for implementation in 2020 in Kyiv differ significantly in regards to singled out thematic areas in the singled out categories (subportfolio) of large projects?

In order to test the null hypotheses about the significance of the difference between the PP projects that were submitted in the categories of small and large projects as defined by request for funding volume, those questions were addressed in the study. We analyzed, accordingly, a database of projects that were the subject of voting in 2019 [10].

It is important to note that the «threshold» that distinguished between small and large categories of projects during this time was lower, at 399 900 hryvnias. At the same time, the lower limit was not actually set, while the upper limit for the category of large projects corresponded to the existing one – 3 000 000 hryvnias. The singled out thematic areas were also somewhat different: security; roads, transport; culture, tourism; ecology; education; health care; social security; sport; IT (information technology); civil society; utilities, energy saving; public space; other.

Our research aimed to show whether a signification difference in the requests for funding volume for projects in various thematic areas within one category existed, and thus, we could assume, it was area specific. It could in its turn indicate “inequality” during their ranking together on the basis of the ratio of the number of votes to the request for funding. This criterion is used in the case of Kyiv. Projects in spheres (thematic areas) with fewer requests for funding volume within a relevant category as subportfolio (small or large) will gain higher ratings in comparison with others, with a slight difference in the votes and, maybe, not in favour. Thus, these spheres (thematic areas) will gain hidden preferences in the form of an increased number of projects accepted for implementation in comparison with other spheres (thematic areas).

Research methodology

To test our hypotheses, we applied a nonparametric criterion, the Kruskal–Wallis test of significance, which is a multidimensional generalization of the Wilcoxon–Mann–Whitney criterion. Since this criterion is rank-based, any monotonic modifications of measurement scales have no effect on it. In accordance with alternative hypotheses, the difference between PP projects, which were submitted under small and large project categories as subportfolios, regarding the request for funding volume is insignificant. After carrying out the calculation by applying the program product IBM SPSS Statistics 22, we rejected each of the alternative hypothesis with a level of significance of 0.05. It means that the difference between PP projects, which were submitted under small and large project categories as subportfolios in the relevant thematic areas, regarding the request for funding volume is significant.

Therefore, it is fair to rank the projects within their thematic areas with budgeting of these areas as singled out categories or to evaluate projects based on the number of votes, where the request for funding volume has no bearing on how they are rated. I.e., in the first case, we deal with a portfolio (subportfolio).

It is obvious that if we introduce ranking by another for a certain thematic area criterion within one common budget, it must be applicable for all units of the single portfolio. As a result, it may have a negative impact on rating results for projects of other portfolio segments, which are singled out in accordance with their spheres (thematic areas).

Our considerations bring us to a logical assumption of the necessity to single out within the public budget portfolio of Kyiv inside of with the existing categories (subportfolios) – small and large – categories (subportfolios) of thematic areas. The latter, as we mentioned beforehand, now may only be considered as subdivisions created for the ease of management.

Model for optimization of the PP projects portfolio

The issue of optimization of a portfolio or subportfolio which corresponds to the existing singled out categories of projects as portfolios (subportfolio) is of special interest during portfolio aligning of PP projects. This issue could be considered through a few aspects. Firstly, it is a possibility to consider the conditions of dependence between separate projects. Within the singled out categories as portfolios (subportfolio), as well as within the subdivisions of these categories, PP projects may be presented as independent or dependent. On the basis of addition or replacement, the latter can therefore be depicted as dependent. In the meantime, by creating new, integrated, components that comprise dependent projects, the conditions of the components' reliance in accordance with these principles can be taken into consideration. When we examine, for instance, the PP projects that were completed in Kyiv in 2019 (planning) and 2020 (implementation) under the category of small projects in the «Education» thematic area, we can see that there were numerous requests for funding in the same amount for projects that were similar but for different schools, and that were intended to install audio and multimedia equipment. These projects can be considered together, for instance, as a program, which are addition in cost. We can expect a positive synergy effect due to the possibility of centralized procurement, with subsequent installation and maintenance appropriate to these equipment projects [10]. The same considerations can be applied when we observe projects for kindergartens «Music and Dances», which were completed in the category of small projects in the thematic area «Culture» in 2019 (planning) and 2020 (implementation) [10].

We could also provide some examples of mutually exclusive projects. For instance, in the thematic area «Education» or «Sport». Some requests for funding equipment for playgrounds and sports grounds, which are located so close to each other, based on «target audience» as a number of residents who will potentially use these sites, can be considered mutually exclusive. The provided conditions of dependence can be partially taken into account during the preliminary examination and, finally, taken into consideration after the rating vote and the optimization process. It is also appropriate to consider the conditions of dependence in the optimization process, based on the definition on the optimization process [3–6], according to the selected categories as portfolios or subportfolios.

The second sensible aspect to consider when dealing with the optimization of the PP portfolio (subportfolio), in our opinion, is the selection of the formulation of tasks for the optimization. First of all, we are to decide whether the optimization will be applied exclusively based on individual ranking, gained by projects according to chosen criteria as a result of voting, or whether the optimization will concern a portfolio (subportfolio) as a whole.

We constantly face an obvious dilemma while forming a list of PP projects for implementation. On the one hand, it is an individual ranking that a project gets based on set criteria, and on the other hand, we deal with the conditions for efficience use of taxpayers' money within allocated budgets. And as we noticed earlier, there might be certain contradictions. By the way, it is worth noticing that the practice of using individual rankings in many cases, including those in accordance with normative acts regulating the public budget in Kyiv, indicates that these ratings are of a pure recommendation nature.

If we deal with the formulation of task for the PP projects portfolio optimization in a category as a portfolio (subportfolio) as a whole, we can apply an integer linear programming method to solve the problem of the portfolio content optimization. The objective function is built on the number of votes given to support separate projects, and it requires maximization. The budget allocated for a certain project category, which under these conditions is considered as a portfolio (subportfolio), serves as a constraint.

According to the above-mentioned statement, we can write:

$$\sum_{i=1}^{I} V_i x_i \to \max, \tag{1}$$

with the constraints:

$$\sum_{i=1}^{I} C_{c_i} x_i \le C_{c_p}, \tag{2}$$

$$x_i = 0,1 \quad i = \overline{1,I}, \tag{3}$$

where V_i – number of votes, given to support the i-th PP project, $i = \overline{1,I}$;

C_{c_i} – capital expenses for the i-th PP project, $i=\overline{1,I}$;

C_{c_p} – maximum value of the capital expenses that can be allocated for the financing of PP projects within the given category as a portfolio (subportfolio);

I – total number of PP projects in the given category as a portfolio (subportfolio).

The constraints mentioned by this model for a PP projects portfolio optimization, expressions (1)–(3), in accordance with accepted practice, do not always take into account the operating expenses, which are linked with operation of PP projects in future. These expenses can be accounted for in different ways. In particular, these expenses may be defined as a total sum for a certain period of project operation, for example, 5 years, and can be taken for as a constraint at the preliminary selection stage. It is also possible to include these expenses – as discounted operating expenses – as a constraint for objective function (1) in the following form:

$$\sum_{i=1}^{I}\sum_{t_e=1}^{T_e}\frac{C_{o_i t_e}}{\prod_{j=1}^{t_e}\left(1+k_{ij}\right)}x_i \le c_{o_p}, \tag{4}$$

where $C_{o_i t_e}$ – the operating expenses for the i-th PP project in the time period t_e, $t_e=\overline{1,T_e}$, $i=\overline{1,I}$;

k_{ij} – cost of capital for the i-th PP project in the time period j, $j=\overline{1,t_e}$, $t_e=\overline{1,T_e}$, $i=\overline{1,I}$;

c_{o_p} – maximum value of the operating expenses that can occur within the given category as a portfolio (subportfolio);

T_e – economic life cycle, that is accepted by PP projects.

The objective function can be supplemented with a constraint on the operating expenses in the form of:

$$\sum_{i=1}^{I}C_{o_i t_e}x_i \le C_{o_{t_e}p},\ t_e=\overline{1,T_e}, \tag{5}$$

where $C_{o_{t_e}p}$ – maximum value of the operating expenses that can be allocated for the given as a category portfolio (subportfolio) in the time period t_e, $t_e=\overline{1,T_e}$.

When, developing the PP projects portfolio optimization model, taking into account the concept of the time value of money by using discount procedure, poses the question of the degree of risk. Project risk refer to risks relating to particular projects included in the portfolio. Structural risk refers to risks relating to the processes used to construct the portfolio and potential conflicts between its components. Global risks refer to risks that are bigger than the sum of risks for individual components [3–6]. As a rule, we take into account the risks of separate projects in their budgets by possibility of increasing the latter by up to 20%. Meanwhile, considering the existence of structural risks and partially global risks in the totality of projects in a certain thematic area will be allowed us, if we shell present components of a certain thematic area as a portfolio (subportfolio).

In this research, we examine, as an example, the requests for funding, which were submitted in the small project category as a portfolio (subportfolio) within the thematic area «Culture» in 2019 [10]. The projects were implemented in 2020. To define the optimal content of the project set of this thematic area as a portfolio (subportfolio), we applied the integer linear programming method, using the add-in program Solver in Microsoft Office Excel 2010. We took into consideration the following indicators for each project: the number of received votes in favour, the request for funding volume, criterion value for evaluation, and ranking. 50 requests in total were selected for competitive selection. 28 projects received the status «implemented» under the conditions of applying the current, based on individual ranking of projects, approach to selecting projects for implementation, the total number of votes in support of these projects amounted to 10 659 votes. The total budget was 3 985 659 hryvnias. In accordance with the proposed, based on portfolio (subportfolio) optimization as on whole, approach to optimization, 27 projects received the status «implemented» (26 of which had this status before). We recommended changing the status of 2 projects to «participated» and, vice versa, we recommended adding one project to the list of projects that could be implemented. The total number of votes in support of these projects amounted to 10 713 votes. The total budget was 3 985 959 hryvnias. Under the condition of using the current approach to the optimization, the number of votes assigned to 1 000 hryvnias of funding for this project set was 2,67, and in accordance to the offered one, 2,69. At the same time, we considered the restriction for funding the projects in this area as a budget, based on the funding volume allocated for implementation of accepted projects, which amounted to 4 000 000 hryvnias.

We need to set a separate budget for the category in order to single out the PP project category and refer to it as a portfolio in the future. For instance, in accordance with the parameters of the public budget of Kyiv for 2022, it is foreseen that 40% of it will be used to implement small projects and 60% to implement large projects. If we introduce separate budgets for thematic areas, we can hypothetically use different variants to allocate budgets for small and large projects for this area. For example, this distribution can be used in proportion to the number of submitted requests or to the number of votes already received based on the results of voting by thematic areas. Other variants are also possible.

If we consider a project as a mean of realization and, under certain conditions, a way to form a strategy for a territorial community, we can apply the level of a weighting coefficient as one which stimulates the development of certain thematic areas. At the same time, it can be either «strengthening» the recognition of strategic areas of development that are important for the territorial community, or strengthening strategic areas that «don't get» funds due to the deficit in the «normal» budget, or searching for new promising areas of strategic development. The latter scenario gives PP projects an experimental feel. We need to deal separately with the issue of the hierarchical structure of PP projects portfolio: categories of small and large projects must be divided into thematic areas, or vice versa, thematic areas must be divided into small and large categories. However, this issue is beyond the scope of this research.

Hypothetically, there may be complaints about the «non-transparency» of PP project selection if we use the portfolio optimization approach. First of all, due to the fact that the portfolio optimization process is not as clear as the rating. Although we would like to note that the rating as it is mentioned in various normative rulings of territorial communities has the character of a recommendation rather than a final decision. At the same time, the correspondent program software used in the proposed approach is an open-source product, which is adopted for maximum ease of use for anyone who is eager to check whether this optimization is carried out properly. Such services are offered worldwide, and in particular in Ukraine for various areas of social life and in the context of solving a wide range of issues.

Conclusion

We have elaborated the concept for aligning of the PP projects portfolio, which is based on research of methodological approaches considered in the relationship to: structuring of categories; definition of criteria for evaluation, selection, and prioritization; and optimization of the PP projects sets as portfolios (subportfolios). We have formulated and verified, using the database for the public projects in Kyiv, hypotheses regarding the significance of differences in the requests for funding volume in the sets of the PP projects singled out by thematic areas in the small and large categories. It has been determined, using the Kruskal–Wallis significance test, that these differences are significant. So, we can see the necessity to present projects of thematic areas as part of the corresponding the subportfolios (subportfolio of large projects or subportfolio of small projects) of the general portfolio of PP projects. The model, based on integer linear programming method, for the aligning of the optimal composition of the PP projects portfolio, which is recommended for implementation, is suggested. Under the present circumstances individual territorial communities of Ukraine could introduce in their thematic areas for public projects such area as protection civilians from affecting of the fighting.

The results can be used for improvement and further development of the methodological support for the aligning processes of the portfolios under the circumstances of the execution of the PP projects, which are regarded as components of the respective portfolios.

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