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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:

$$C = \left(M \times R\right). \tag{1}$$

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:

$$P = \left\{ p_1,\ p_2, \ldots, p_n \right\}. \tag{2}$$

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.

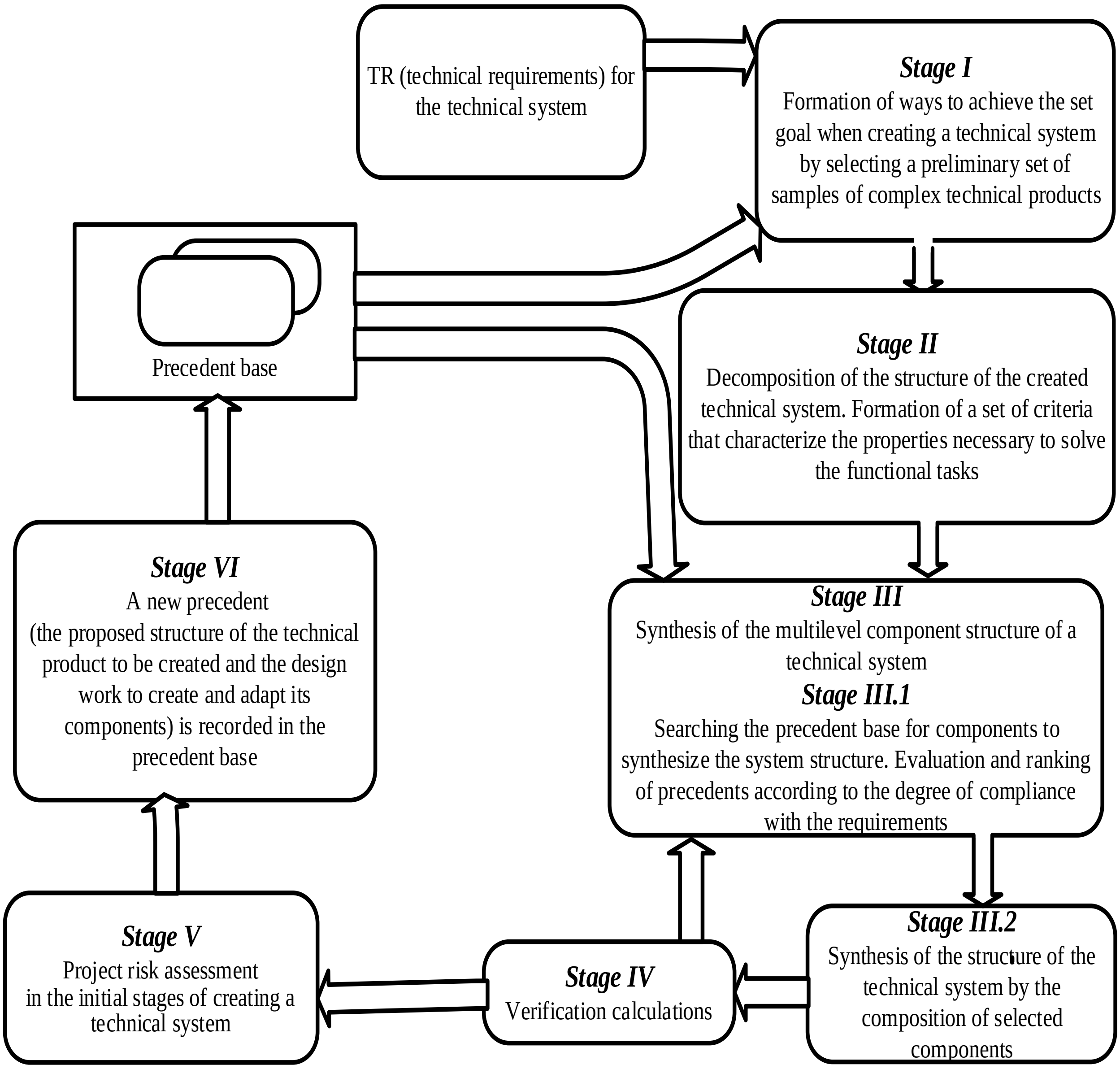

Fig. 1. Scheme of the method of synthesis of a complex technical system using the positive experience of previous developments

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:

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

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:

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

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:

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

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

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

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

$\delta_0\left(\{i\},\{i'\}\right), \delta_1\left(\{i\},\{i'\}\right), \ldots, \delta_{h-1}\left(\{i\},\{i'\}\right)$ – 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 $X_0, X_1, ..., X_{|I|-1}$.

Start. 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:

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

Step $h=1$. 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:

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

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

$$X_1 = X_1(I) = X_0 \cup a_1, \quad (7)$$

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

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:

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

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

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

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

Step $h = Z$. 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:

$$N = |I| + h,$$

$$a_h = s_h \cup s'_h,\ Si(a_h) = \{s_h,\ s'_h\},$$

$$X_h(I) = X_{h-1}(I) \cup a_h,$$

$$M(X_h(I)) = M(X_{h-1}(I)) \cup \{a_h\} \setminus \{s_h\} \setminus \{s'_h\}, \qquad (11)$$

$$\nu(a_h) = \min\{\delta_{h-1}(s,\ s');\ s \neq s',\ s,\ s' \in M(X_{h-1})\},$$

$$|a_h| = |s_h| + |s'_h|.$$

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:

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

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:

$$C_j^u = \left\{ \left\{ C_1^{u+1} \right\}, ..., \left\{ C_i^{u+1} \right\}, ..., \left\{ C_{n_u}^{u+1} \right\} \right\}, \qquad (13)$$

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:

$$C_j^u = \left\langle h_1,\ h_2, ..., h_{s_{ju}} \right\rangle, \qquad (14)$$

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:

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

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.

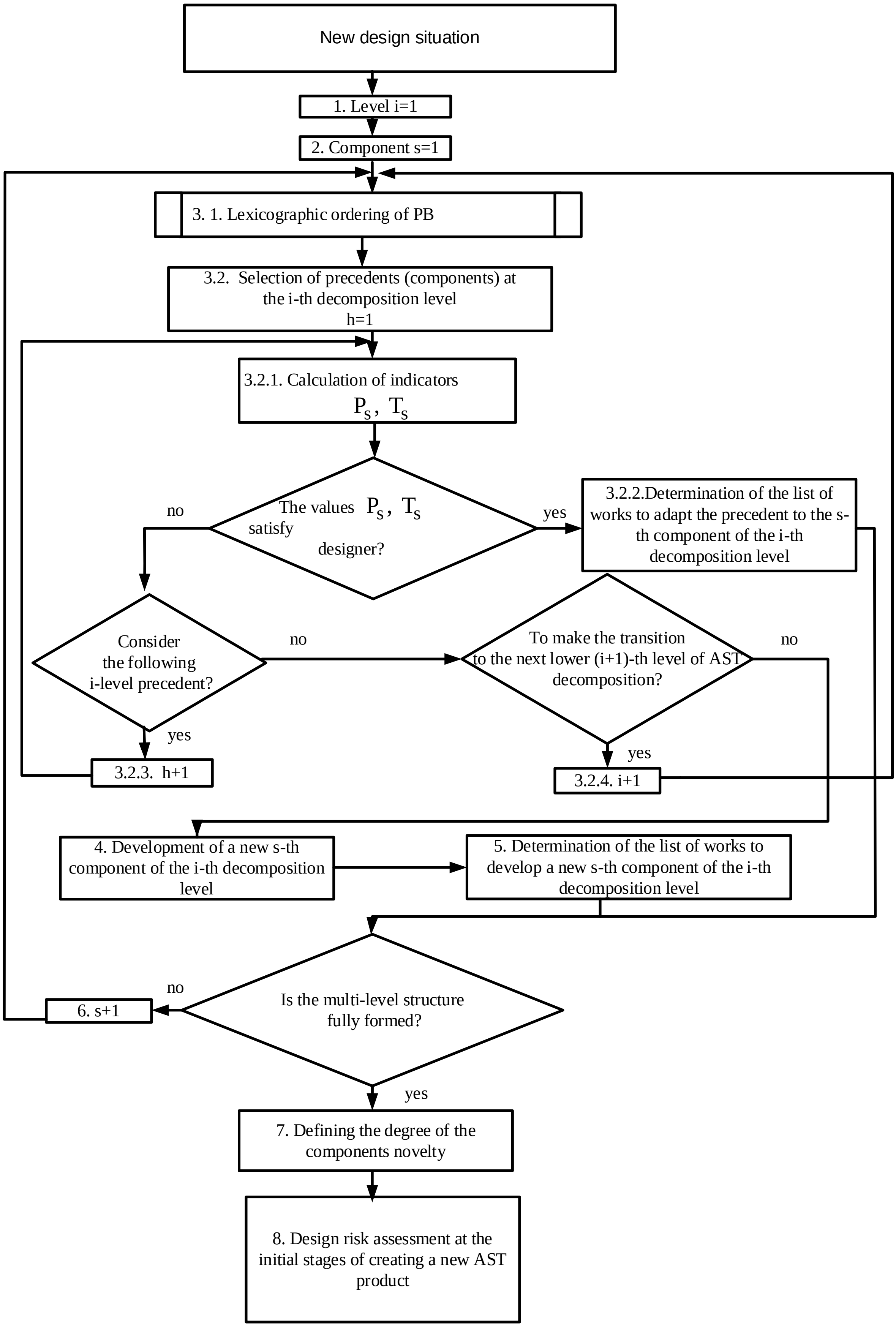

Fig. 2. Schematic diagram of the system synthesis method for the multilevel component architecture of an AST product

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.

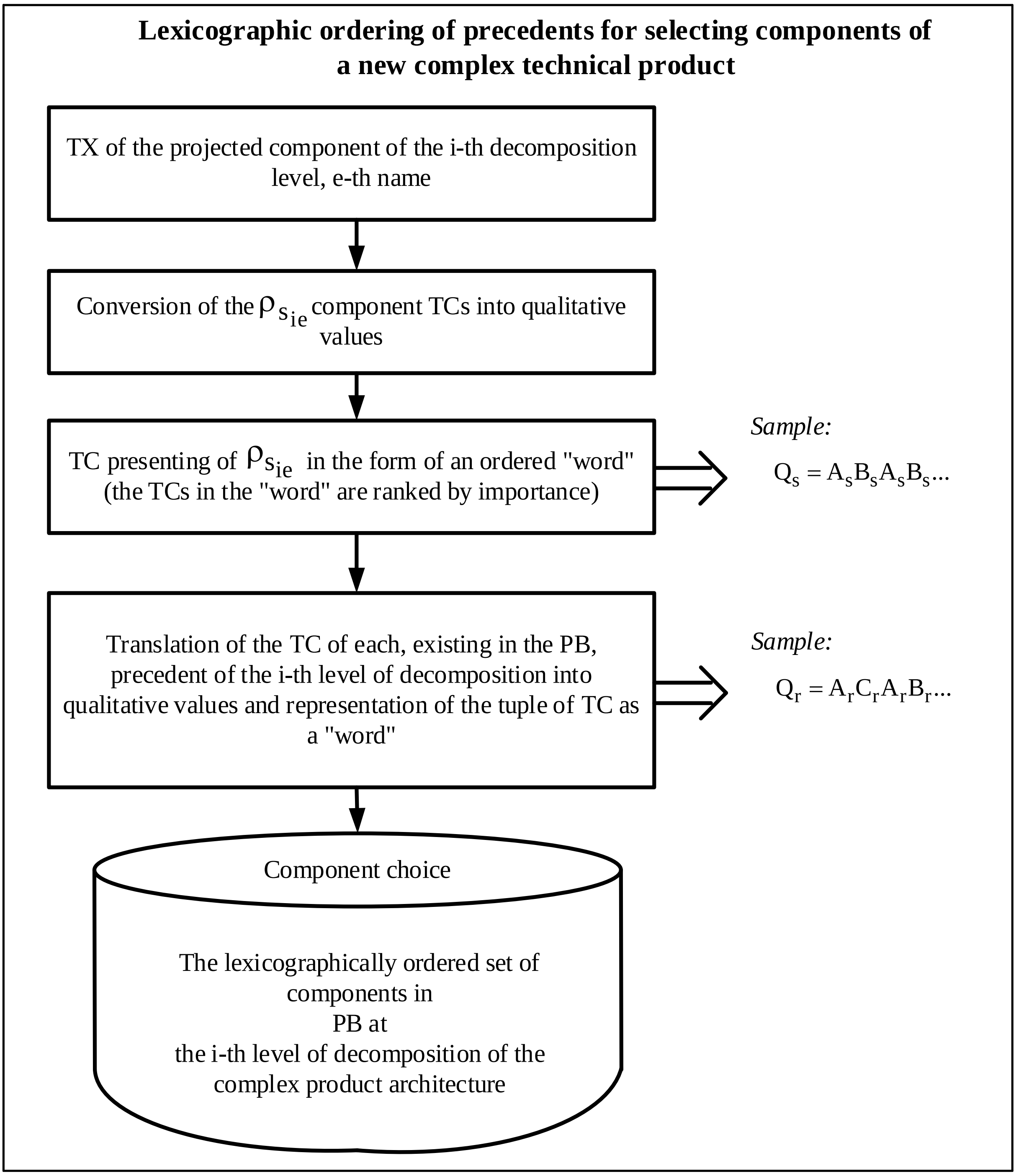

Fig. 3. Scheme of lexicographic ordering in the hierarchical precedent base to form a multilevel component architecture of the AST product

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:

$$r_i = r_i^{'} + n_i, \tag{30}$$

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 $i+1, i+2, \ldots$ 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:

$$G^i = \bigcup_{ji} G_{ji}^i, \tag{31}$$

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:

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

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:

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

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, $t \in \{\text{RUC}, \text{MRUC}, \text{IC}\}$) 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 $g_{jtw}(r_j, s_{jt})$, 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:

$$(a_1, b_1, c_1) \cdot (a_2, b_2, c_2) \equiv (a_1 \cdot a_2, b_1 \cdot b_2, c_1 \cdot c_2) \quad (38)$$

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

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

where $\mu_{N_r \cdot N_s}(u)$ – 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; (a, c) – 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:

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

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 $R_f^{пр}$:

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

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:

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

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

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

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:

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

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:

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

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:

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

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

Here it is necessary to consider the condition $n_{1_i}+n_{2_i}+...+n_{r_i}=n$, 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:

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

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.

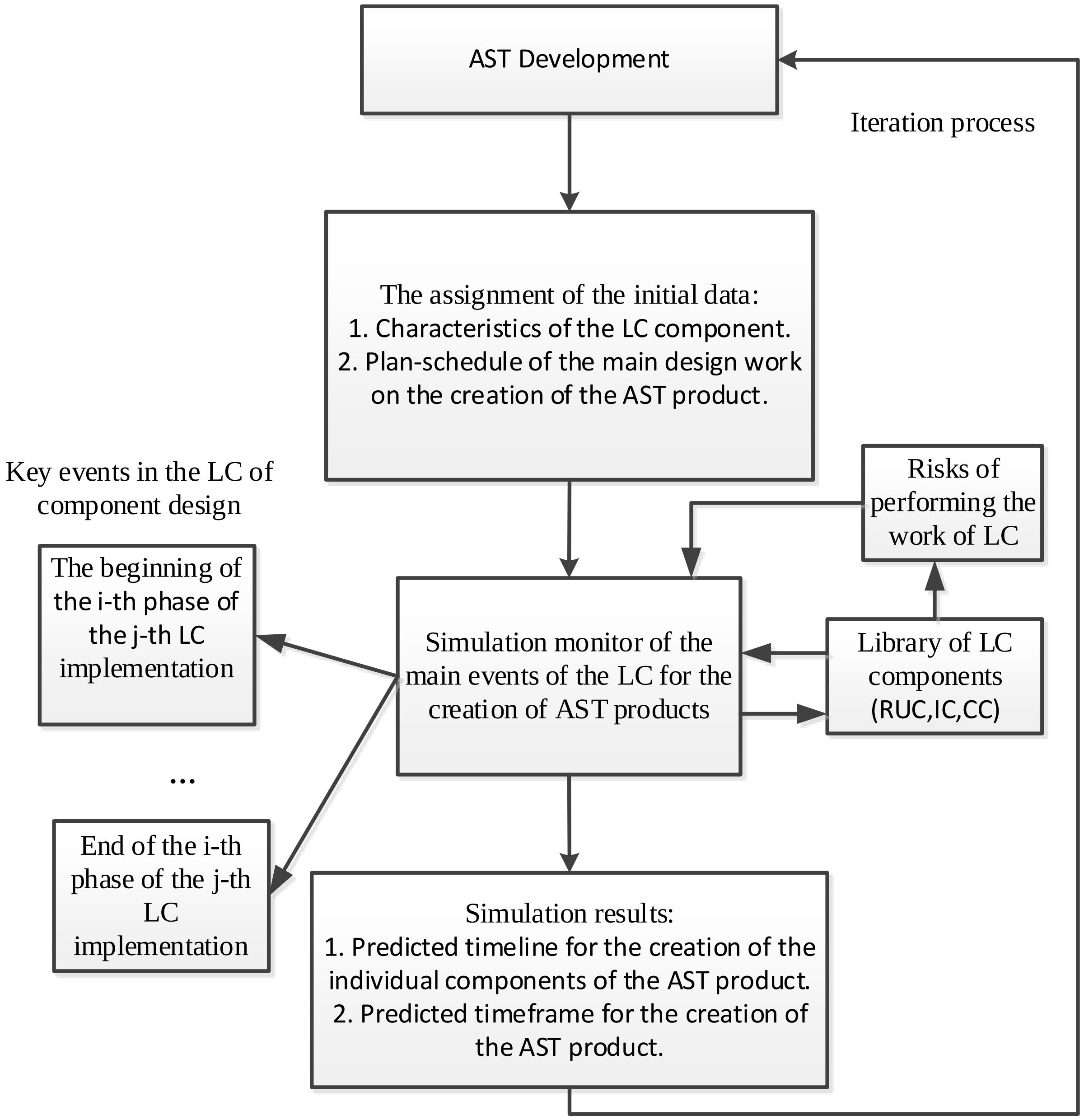

Fig. 4. Structure of the simulation event model

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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