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The Method of Variant Synthesis of Information and Communication Network Structures on the Basis of the Graph and Set-Theoretical Models

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***Abstract*—**The subject matter of the article is developing information and communication network (ICN) for critical infrastructure systems (CIS). The aim of the work is to provide high-quality information and telecommunication processes by developing the optimal version of distributing CIS functional tasks and ICN processes to the network nodes. The article deals with following problems: developing a model for mapping the information and technical ICN structures, developing a method for variant synthesis of ITS structural models, a formalized representation of the problem of selecting CIS optimal structure. The methods used are: the system method, the set-theoretic and graphic analytic approaches, methods of hierarchic structures synthesis, optimization methods. The following results were obtained: the use of system approach for formalizing the information processing process in CIS was justified; mapping the ICS functional system into the information and technical one was presented as multilevel graph chain; the generalized representation of graph structures hierarchy was developed for the set of data transmitting tasks; this approach enabled formal representing alternative variants that consider the main links, sequencing, the amount and flows of the processed information among the different structure levels; the scheme of variant synthesis method of ICN models according to graph structures mapping was developed; the problem of selecting optimal ICN structures was formally presented; a complex efficiency criterion for solving problems of optimizing variant synthesis of structures; the problem of optimal synthesis of the structure of the given level factored in resource constraints was formulated. Conclusions. The article deals with such novelty aspects as improving the model of problem of selecting the optimal ICN structure by set-theoretic formalization factored in the criterion of maximum intensity of computational resource application, which enabled determining structural links among the major elements considering the decomposition of the model up to the basic elements such as "node" and "task" and the development of a new method of optimal ICN structuring which unlike the existing ones involves the variant synthesis of structures hierarchy and formalizing selection problems on the basis of set-theoretic models, which enables providing the efficiency of application of information and technical net resources.

***Index Terms*—**Information and communication network, structure synthesis, graph representation, selecting,

mapping, set-theoretic model, software.

I. Introduction

With the development of high technologies, the range of high-risk facilities that belong to the class of critical infrastructure systems (CIS) is expanding. For example, thermal, nuclear and hydroelectric power stations, high-speed ground and air transport, defense and space systems. The challenge for such systems is to provide quality information and telecommunications processes. In the context of continuously improving concepts of developing information and communication networks (ICN), in the face of new network technologies, there is the tendency of their "convergence", i.e. amalgamating into more complex structures and technologies. There is the convergence of infomedia different in origin and operation principles.

Despite the rapid development of physical and channel-level technologies, the full potential of ICN can be realized only due to effective managing available network resources in the face of increasing demands for the operability of information exchange. This determines the necessity of searching new approaches to determining the physical and functional structures of the network.

II. Problem Analysis and Setting the Problem

When building distributed and local information and communication networks, there is a number of unresolved problems which are complex scientific and technical issues. Considering the ICN hardware and software these problems can be grouped to:

- develop a reliable ICN on the basis of available hardware and software that now consist of isolated and unequal components;
- turn to promising technical and software tools step by step.

At the first stage, when installing software complexes on separate ICN fragments, it is necessary to distribute CIS functional tasks to the nodes of the base fragment, taking into account the heterogeneity of the nodes, the heterogeneity and inequality of hardware and software. It is necessary to keep in mind that the requirements of operability, reliability, continuity and completeness of information for these systems are of primary importance. [1]

Many publications deal with the analysis and synthesis of ICN [2 – 7]. The classical mathematical models based on the results of graph theory and the theory of mass service [3] do not take into account the dependence of net structure characteristics on the parameters of applied problems that are solved in a networked environment, which leads to a loss of accuracy in the results of modelling.

The analysis of the literature showed that the majority of the mathematical models that assume the operation of software complexes in a multiservice network environment do not take into account the heterogeneity of the basic hardware and software support tools of the ICN [6 – 9].

One of the promising areas of ICN development is the service-oriented approach that enables investigating the processes of information exchange among the network nodes involved in solving various functional tasks and supporting various information processes. This approach enables more adequate modelling of data flows in multiservice ICN. However, the formalization presenting data streams in this approach is still insufficient and is limited to modelling individual tasks and aspects of ICN operation [10, 11].

Therefore, the purpose of this article is to develop a formalized model and a method for synthesizing ICN structures that enables developing an optimal version of distributing CIS functional problems and ICN processes to the nodes of the basic fragment of the network.

III. Problem Solving

A large number of elements of CIS subsystems and the functions they perform, a high degree of elements interconnection, the complexity of algorithms for selecting particular actions for controlling real-time processes, large amounts of processed information determine ICN that enables CIS operating as a complex system [8]. The synthesis of the structure of a complex system requires developing the following formalized models;

a) he models of the controlled system structure for determining the optimal composition and interrelations of the systems elements, the optimal partitioning of the set of controlled objects into separate subsets that have the specified characteristics of the relations;
b) the model of the control system structure for solving the problems of variant choice: a number of levels and subsystems, the organizational hierarchy, for determining the principles of management organization and the optimal distribution of performed functions among different system components;
c) the model of the structure of data transmission and processing systems factored in the composition of the hardware and software of the telecommunications network.

When developing a model for the hardware and software structure, it is necessary to consider the following points [8, 12, 13]:

- determining a set of ICN nodes and connections among them;
- distributing tasks assigned to the technical means of ICN to the levels and nodes of the system;
- selecting ICN technical means that provide the effective solution of CIS tasks.

The above problems of the synthesis of models of ICN structure are closely related to the tasks of optimizing its functioning: to determine the composition of nodes, that is optimal in reference to the complex functional of efficiency, as well as the structure of the interrelations among them for the given set of CIS functions [15].

In accordance with the system approach for building the model of information processing in ICN, it is necessary to determine the management objectives and functional tasks in CIS, information and communication processes for completing tasks, dataware and software, to distribute tasks, processes and support elements to the nodes of the system and, in accordance with this, to determine the complex of technical means.

If there are some problems of heavy load for some elements of the system structure, it is necessary to take into account the rules of their functioning. These rules are determined while modelling the system since the distribution of functions and relationships in the system depends on them.

When constructing a model of the information processing process, the following selection problems should be solved:

- selecting typical subsystems, tasks, CIS modules for determining functional and information tasks, system nodes and their interrelations;
- selecting options for building ICN nodes and their location;
- selecting options for performing various types of CIS functional tasks;
- selecting options for ICN constructing factored in mapping the set of CIS functional tasks and information processes for their implementation in a set of interconnected ICN nodes;
- selecting variants that are optimal in reference to the criterion of efficiency for constructing CIS structure.

To formalize the data for selecting problems the graph and set-theoretical representation is suggested. Thus, the alternative-graph model of the process of information processing is the basis for describing the process of synthesizing the ICN structure and software.

Let $G_S = (S, \Gamma_s)$ graph define a set of interrelated functional problems of a distributed CIS, where S is a set of graph vertices that correspond to individual problems, Γ_S is a set of arcs that show the relationships among them. For $s_i \in S, i = \overline{1,n}$ the graph of the implementation of the tasks of information and communication support $G_I = (I, \Gamma_I)$ is built. Thus, mapping the set of vertices of the graph $s_i \in S, i = \overline{1,n}$ in the set of vertices $i_j \in I, j = \overline{1,m}$, $G_S \to G_I$ is obtained. This mapping implements the functional structure (FS) of the CIS and ICN complex.

The tasks of information and communication support are solved with the help of a set of system and application software. Accordingly, at the next level, for each element $i \in I$ there is a graph $G_P = (P, \Gamma_P)$ of a set of elements of the used software (SW) $p_k \in P, k = \overline{1,l}$; Γ_P is a set of arcs that show the relationships between them. Mapping the set of vertices of the graph $i_j \in I, j = \overline{1,m}$ in a set of vertices $p_k \in P, k = \overline{1,l}$, $G_I \to G_P$ is obtained.

The graph of a set of information support elements (specialized and local databases) is denoted as $G_B = (B, \Gamma_B)$, where B is a set of vertices of the graph corresponding to the elements of information support; Γ_B is a set of arcs reflecting data relationship. Mapping a set of vertices of the graph $p_k \in P, k = \overline{1,l}$ in a set of vertices $b_m \in B, m = \overline{1,f}$, $G_P \to G_B$ of functional structure in ICN information structure is obtained. This mapping implements ICN information structure (IS).

Thus, mapping

$$\left(G_S \to G_I\right)_{FS} \to \left(G_P \to G_B\right)_{IS}$$

is formally represented as a multilevel chain of graphs mapping.

To implement information and communication tasks, ICN technical structure should be developed. Graphs $G_U = (U, \Gamma_U)$ that are the variants of realization of the local networks structure are defined as ICN nodes, where U is a set of vertices of the graph corresponding to the nodes of the network; Γ_U is a set of arcs reflecting the system of switching nodes. Mapping a set of vertices of the graph $i_j \in I, j = \overline{1,m}$ in a set of vertices $u_c \in U, c = \overline{1,d}$, $G_I \to G_U$ is obtained.

For a variety of options for ICN technical structure a variety of options for data transmission, that is traffic management, [16, 17] should be determined. Graph $G_T = (T, \Gamma_T)$ i.e. the options for implementing data flows as information links, where T is a set of vertices of the graph corresponding to the nodes of the network, and $T \subset U$; Γ_U is a set of arcs representing the system of knot commutation, $\Gamma_T \subset \Gamma_U$. Mapping the set of vertices of the graph $u_c \in U, c = \overline{1,d}$ in a set of vertices $t_h \in T, h = \overline{1,z}$, $G_U \to G_T$ is obtained. This mapping implements ICN technical structure (TS).

Mapping ICN functional structure in the information and technical one is represented as a multilevel chain of graphs:

$$\left(G_S \to G_I\right)_{FS} \to \left\langle \begin{matrix} \left(G_P \to G_B\right)_{IS} \\ \left(G_U \to G_T\right)_{TS} \end{matrix} \right.$$

After the synthesis of the options for ICN technical structure, the software and information support should be assigned to the nodes of the network factored in the channels of information interaction. The result can be represented as a mutual mapping of the following sets:

$G_P \leftrightarrow G_U$ is options for assigning application programs to network nodes for solving specific functional tasks;

$G_B \leftrightarrow G_T$ is definition of data flows at a variety of information relationships.

Taking into account the mappings mentioned above, which can be generally represented by functions φ1 … φ6, graph model of the synthesis of ICN structures looks as follows:

$$\left(G_S \xrightarrow{\varphi_1} G_I\right)_{FS} \xrightarrow{\varphi_2} \left\langle \begin{array}{c} \left(G_P \xrightarrow{\varphi_3} G_B\right)_{IS} \\ \varphi_5 \updownarrow \qquad \updownarrow \varphi_6 \\ \left(G_U \xrightarrow{\varphi_4} G_T\right)_{TS} \end{array} \right.$$

In particular, for a complex of data transfer tasks, a generalized representation of the graph structures hierarchy is shown in Figure 1. Here, set S represents the structure of probable realizations of CIS basic functional problems. Consequently, for each variant of implementation S, different variants of numerous dataware and software tasks, application programs and databases, as well as ICN nodes and data transmission facilities are considered.

According to the system approach, the scheme of the method of variant synthesis of ITS structural models as described by mapping graph structures (Fig. 1) is schematically shown in Fig. 2.

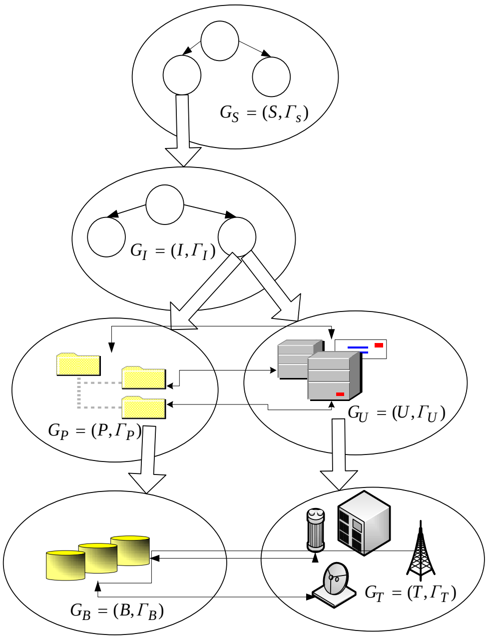

Fig.1. Generalized representation of the hierarchy of ICN graph structures.

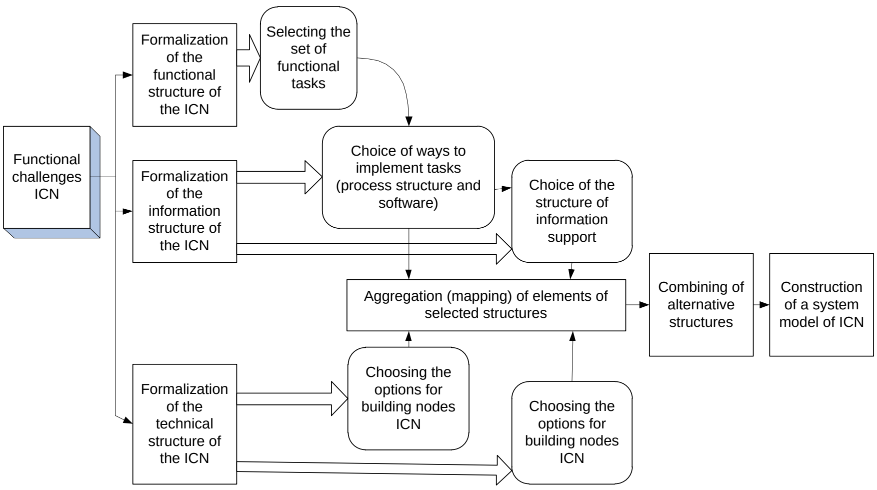

Fig.2. Scheme of the method of variant synthesis of ICN Structural models

It should be noted that, the relationships that reflect the sequence, amounts or flows of transmitted information are considered while formalizing the relationships between tasks or stages.

The system approach assumes that when the formalization of the process of information processing in a complex system changes to the model of its functioning, the following stages should be necessarily performed:

- modelling all admissible variants of initial data allocation;
- modelling all variants of task placement among the system nodes;
- distinguishing and analyzing partially isolated components of the system and constructing appropriate models.

According to the above scheme of the method the initial sets are represented in the mentioned models by the elements of the graph structures S, I, P, B, U, T; while mappings that determine the relationships of the structures as:

$$\varphi_1 : G_S \to G_I$$
$$\varphi_2 : G_I \to (G_P, G_U)$$
$$\varphi_3 : G_P \to G_B$$
$$\varphi_4 : G_U \to G_T$$
$$\varphi_5 : G_P \leftrightarrow G_U$$
$$\varphi_6 : G_B \leftrightarrow G_T$$

Considering these mappings, the problem of selecting ICN optimal structures can be formally represented.

The elements of the graph structures I, J, L, M, P considered above are greater and include tasks, software, data, technical objects, communication facilities, etc. However, the above graph of alternative structures assumes such hierarchical sequence of the elements of structures where the subsets of homogeneous objects are detailed at the same level of hierarchy.

In such a case the correspondence which is important for the synthesis of structures should be set up among them, considering one of the two options:

- distinguishing such a variant (among the set of admissible variants) that will enable achieving the required properties in the context of specified criteria for optimality grounding on a set of required properties of the structure;
- analyzing the probability of achieving ICN required properties grounding on characteristics of the structure.

In consideration of the foregoing, ICN information structure can be determined by a set of the following parameters:

- N, that is a number of working users;
- M, that is the amount of nodes used;
- D, that is a number of system applications being used;
- L, that is the amount of tasks being solved;
- R, that is a number of databanks being used.

Besides, it is necessary to determine:

a) Z, that is a data tuple which describes tasks Z and sets the matrix lines which describe the interrelations of the tasks:

- with system applications – P,
- with databanks – D,
- with users – U;

b) the sequence of executing system applications by specific tasks – Wk;
c) a set of descriptions of data amounts –Akm, which are necessary for system applications while using them by specific tasks, and consist of matrix lines of data amounts Vk and Bk;
d) the matrix of system application assignment to the net nodes – G;
e) the matrix of connecting users to the nodes – H;
f) the matrix of databases allocation to the nodes – S.

This set definitely determines the information structure of an information and communication net.

Let us specify a set of parameters that determine the net information structure as SI. Thus, we have:

$$SI = \{N, M, D, L, R, S_i, A_{km}, G, H, S\},$$
$$S_i = \{p_i, d_i, u_i, W_i\},$$
$$A_{km} = \{v_{km}, b_{km}\}.$$

The major elements of the information structure and their parameters are shown in Fig. 3.

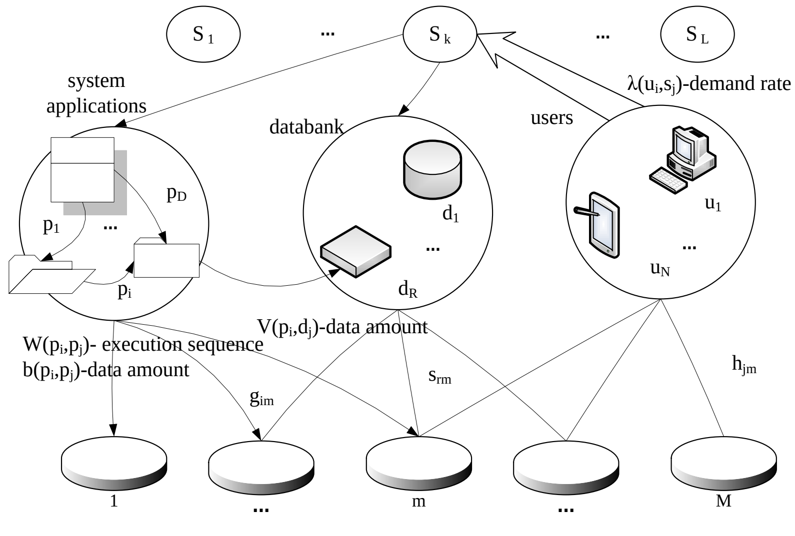

Fig.3. The diagram of the major element and parameters of the model of ICN information structure

It should be noted that if system applications and databanks are compared according to their allocation to the net nodes (the rules of developing G and S matrices), databanks can be considered as system applications in the context of theoretical studies of the network. This approach enables simplifying the obtained data greatly and making them more descriptive.

Keeping in mind that all possible variants of the information structure of the network can be described in the foregoing manner, it is necessary to formalize the procedure for selecting the optimal structure, which is a sequence of particular selection problems.

Let a set of variants of ICN representation be denoted as:

$$S = (S^0, S^1), S^1 = \{s_{ik}\}, i = \overline{1,m}, k = \overline{1,m}$$

where S^0 is the initial state of the model, which is determined by the functional tasks of the entire system;

s_{ik} is the state of the model of ICN structure at the k^{th} level of the hierarchy after the solution of the i^{th} selection problem.

Let a set of modelling steps be determined as:

$$H = (H^0, H^1), H^1 = \{h_{ik}\}, i = \overline{1,m}, k = \overline{1,m},$$

where H^0 is the action necessary to change solving the tasks of CIS functioning to solving the tasks of ICN functioning;

h_{ik} is a set of steps for modelling the solution of the i^{th} task at the k^{th}, that represent such series of steps which result in the transition to the $(k+1)^{th}$ level of the hierarchy of the object structure being modelled.

Then the following relations are correct:

$$\left[s_{i(k-1)}, s(h_{ik})\right] \Rightarrow s_{ik};$$
$$\left[h_{i(k-1)}, h(s_{ik})\right] \Rightarrow h_{ik},$$

where $s(h_{ik})$ is additional data for the model obtained by performing step h_{ik},

$h(s_{ik})$ is the step selected according to the state s_{ik}.

To select step h_{ik} all the states of the model of the complex $\{s_{ik}\}, i = \overline{1,m}, k = \overline{1,m}$ should be built.

Let the procedure for selecting the step at the k^{th} level be denoted by V_k. Then $s_k \xrightarrow{V_k} h_k$, where $s_k \in S$ is a set of admissible states of the model at the level k. If step h_k is not appropriate, the procedure of re-selecting is necessary. This procedure will be denoted by V_k*. Then $s_k \xrightarrow{V_k*} h_j$, where $j = \overline{1,k}$, $k \le m$. Combining the expressions obtained, the process of selecting the step can be denoted by the expression:

$$h_j = \begin{cases} V_j(s_j), \text{ если } V_k*(s_k) = j, j < k \\ V_k(s_k), \text{ если } V_k*(s_k) = k \end{cases}$$

Subset S" of the end states of the system model is selected in set S. Then subset S" is split into two more subsets of the second level:

$$S" = (S"_+, S"_-),$$

where $S"_+$ is a subset of the end states satisfying CIS safety conditions;

$S"_-$ is a subset of the end states that are characterized by a significant level of risk.

The i^{th} selection problem while synthesizing ICN structures factored in the state of the model is denoted as the tuple

$$Z_i = \langle S_i, H_i, V, W, i \rangle,\ S_i \subset S"_+,\ H_i \subset H,\ i = \overline{1,m}.$$

In this case, the initial selection problem is defined as:

$$Z_0 = \langle S^0, H^0, V, W, 0 \rangle.$$

Then the variant synthesis of structures lies in the sequential transition from the solution of problem Z_0 to the solution of a certain problem Z_m, when the model changes to state $S^m \in S"$. In this case, if $S^m \in S"_+$, the execution of the sequence of states $S^0, S^1, .., S^m$ is a global task of synthesizing the structures of the target network. Let Z'_n be its solution, then the set of all such solutions is:

$$Z' = \{Z'_n\}, n = \overline{1,m}$$

The specified set should be estimated according to the complex criterion of ICN efficiency. Then the formal model of the problem of optimizing the variant synthesis of structures is represented by the tuple

$$\Psi = \langle Z_0, Z, Z', F \rangle,$$

where F is the complex efficiency criterion.

Let us consider ICN structure at the level of the processes and tasks of applied software (set P). Within model M, the sets of tasks that must be performed by the ith elements will be denoted as $P^i = p_k^i, k = \overline{1,l}; i = \overline{1,m}, P^i \in P$.

Let us assume that the execution of each process from $p_k^i \in P^i$ requires the consumption of information and computing resource M_k^i that is subject to optimization and represented as a hierarchy subordinate to applied processes. To consider repeatedly performed processes, the coefficient a_k^i is introduced. Then the process p_k^i will be executed while consuming information and computing resources in the amount of $a_k^i M_k^i$ that is subject to optimization.

Pair (P_j^*, j) is called the state of the j^{th} level, where $P_j^* \subset P^i \subset P$ is a subset of the i^{th} level tasks that can be performed together without exceeding the level of magnitude M^i . Let $M^i(P_j^*)$ be the information and computational resource consumption in the state with number j.

Then

$$\Delta_j^i = M^i - M^i(P_j^*) \geq 0$$

The process of synthesizing the ith level structure consists of changing the sequence of states $(P_1^*,1),(P_2^*,2),...,(P_j^*,j_i)$, which is carried out in such a way that the optimization problem according to the local criterion Fi is solved.

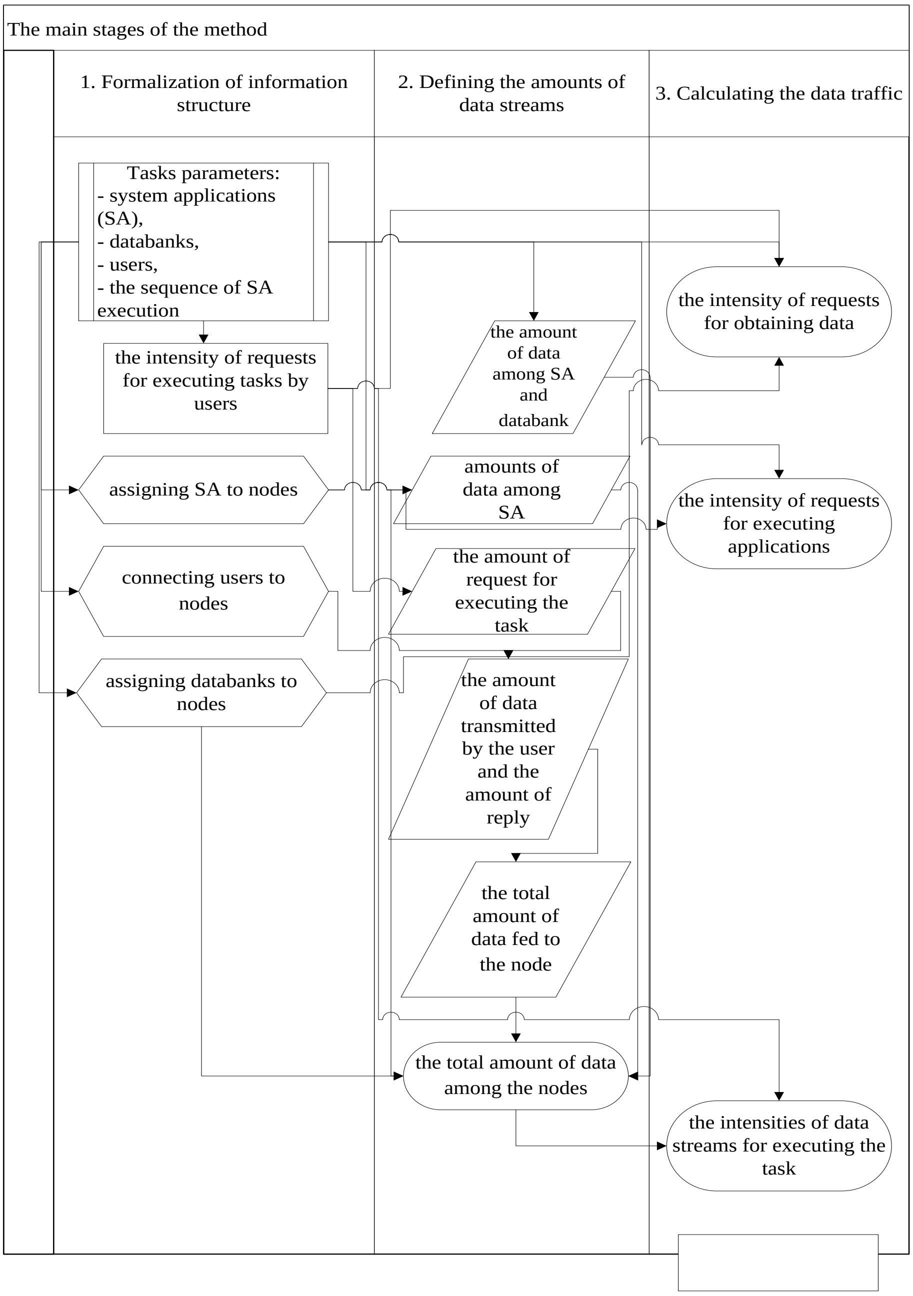

Fig.4. Scheme of the method of determining the parameters of data flows in the context of the fixed information structure of the net

However, it is necessary to take in account a number of external constraints that arise during the execution of the process $p_j^i \in P_j^*$, which are denoted by $D^i(P_j^*)$. In particular, vector $D^i(P_j^*)$ may include resource component M^i. Then the problem of optimal synthesis of the ith level structure factored in external constraints is defined as follows: to find a way to form sets $P_1^*, P_2^*, ..., P_j^*$ in the model environment Ψ, where

$$\sum_{j=1}^{l_i} \Delta_j^i \to \min, \qquad D^i(P_j^*) \leq D^i, j=\overline{1,l}.$$

The formalization of selecting optimal structure of a multilevel ICN that enables CIS functioning makes construction of corresponding ICN models possible.

After the optimal alternative of the net information structure has been selected, the parameters of data flows should be assigned among its nodes while solving a particular task. These intensities are determined by the intensity of the task execution considering all the users of the net (system). It is believed that each application which is used while executing the task is run once only.

The method of determining the parameters of data flows in the context of fixed information structure of the net is shown in Fig.4. The method suggested enables assigning the intensities of data flows to the system nodes. Under these conditions the types of interrelations among the elements of the information structure of thenet and its source data about the amounts of transmitted information are given in Table 1.

Table 1. Parameters of the amounts of transmitted data among the elements of ICN information structure

Parameters	Means of communication	Symbols
The amount of data transmitted by the user	user - nodes	μ_m, $(m = 1,2,\dots,D)$
The amount of task demand	user - task	φ_{0mk}, $(k = 1,2, \dots,L,$ $m = 1,2,\dots,D)$
The amount of responses to the user	task - user	φ_{1mk}, $(k = 1,2, \dots,L,$ $m = 1,2,\dots,D)$
Total amount of data transmitted by users	user - node	v_j^0, $(j = 1, 2, \dots, M)$
Total amount of data received by users	node - user	v_j^1, $(j = 1, 2, \dots, M)$
Total amount of data fed to the nod while executing the task	task - node	π_j^0, $(j = 1, 2, .., M)$

IV. Conclusion

To formalize the process of processing information in CIS the application of the system approach is justified. This approach enabled distinguishing the structural components of selecting structures in ICN environment and to construct a hierarchical graph of alternative formalization that considers the main relationships that reflect the sequence, amounts and flows of information that is processed among different levels of structures. The construction of this graph is the basis for developing the method for building the optimal structure of ICN.

The means for formal description of ICN information structure were developed; these means definitely determine the parameters of applications and their interrelationship. The basis is the complex mathematical model whose components describe the information structure, data flows and the technical structure of the net. The major parameters of the model of the net information structure which is the basis for developing the models of data flows are described.

The article deals with the following novelty aspects:

- improving the model of the problem of selecting ICN optimal structure, by means of set-theoretical formalization considering the criterion of the maximum intensity of using the computational resource, which enabled determining the structural links between the basic elements factored in the decomposition of the model to the basic elements "node" and "task";
- developing a new method of building ICN optimal structure which, unlike the existing ones, assumes the variant synthesis of hierarchy of structures and formalization of selection problems on the basis of set-theoretic models, which makes it possible to ensure the efficient use of information and technical resources of the network.

The formalized model of ICN information structure helped determine the methods of computing a set of parameters and characteristics that describe in particular: the intensities of flows of users’ requests, the intensity of data flows among information nodes, loading to the net nodes, the intensities of flows of request to the databank.

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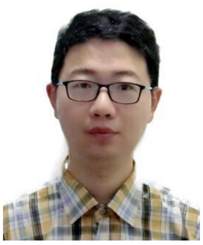

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