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New Approach to Assessing Structural Complexity

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Abstract. The work is devoted to solving a scientific problem of the development of methodology for improvement of multifunctional computing devices structures, which are the components of complex computer systems. Multifunctional data that are generated, transformed, transmitted, stored, processed and used in modern distributed IoT systems is defined. The use of this data simplifies the operations to be performed. New theoretical and applied bases of evaluation and calculation criteria of structural complexity of the created and applied components of complex distributed computer and cyber physical systems are determined and the existing ones are developed that allowed improving system characteristics of computerized systems components and using them efficiently in cyber physical systems due to the reduction of structural, hardware and time complexity.

Keywords. Structuring, structured multifunctional data, structural complexity criteria, distributed computer systems, functional, structural, entropy complexity.

1. Introduction

Information telecommunications systems and IT technologies for data generation, transmission, processing, storage and use are considered to be an important functional environment of modern society.

The concept of multifunctional data (MFD) refers to a wide range of information message types in physical, logical and virtual data environments, for example, analog and digital output sensor data and analog-to-digital converter output data, digital output compression encoder data, data on encryption and protection against errors, output data of special-purpose processors and controllers of digital information processing, modulated and manipulated signals of data transmission systems, physical and logical data in databases and knowledge bases, alphanumeric data, graphic information.

Advanced computer equipment can be developed due to the extension of its multifunctional characteristics by integrating algorithms, calculations and component structures of the computer system processors.

This research work focuses on the development of the method for assessing the structural complexity and a set of performance criteria, which is a completely new issue topic in scientific literature. This approach makes it possible to solve the applied

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problems of comparing the structural complexity (SC) of different classes of data in order to improve their system characteristics, in particular, the time and hardware complexity of digital data generator structures, computing tools, algorithms, methods for multifunctional data encoding and converting.

Well-known scientists such as J.Martin, Thomas J. Harrison, A.S.Wilsky [1-3] pioneered certain issues of the theory of structural complexity development of various data classes.

Among modern scientists, investigating the above issues, Saeed V. Vaseghi, Dean Walter, Jukka Suomela, R. Miller, and others should be mentioned [4-11].

These ideas can also be found in monitoring and control systems and in the field of data protection, when transmitting signals in measuring channels [12-16].

However, the conducted review of literature has shown that the system of structural complexity criteria and a generalized approach to the problem of developing theoretical foundations, methodology, and methods of analysis and improving the structural data organization in computer systems were almost not considered in research works. Therefore, it became the subject of our research.

The purpose of the research is to develop a method for assessing the structural complexity of multifunctional data. This makes it possible to optimize the system characteristics of data and structural solutions of hardware and software in complex computer systems.

2. Concept of Data Structuring

The concept of structuring is associated with the processes of development and improvement of information systems: "Development aims not only at something complex but also at real World, i.e., structured under its realities." "Because everything that exists in the world is structured under its realities." [17].

The fundamental example of information conglomerates structuring is the structure and DNA information organization that demonstrates the role of selection and system survival of structurally more stable and informationally improved forms of living matter. This fundamental theoretical and logistical basis is the entropy principle of optimality. Therefore, understanding the concept of processes structuring, information data and generalization of fundamental theoretical bases is an urgent problem.

The rapid development of modern information technology, computer networks and computer systems set a research of structuring in given branch as the most promising task since almost all trends of modern civilization are closely related to the informatization of society and the proper structuring of information flows.

It is necessary to know the system structuring to better understand the role of information and use it effectively when operating. The highest level of information structuring is its singling out as a system for a particular item and associated subsystems. However, any system can be broken down to identify its indivisible units.

2.1. Classification of Attributes and Formalization of Data Structuring Processes

Statement of the concept of solution to the problem of information processes structuring allows us to generalize the fundamental theory of structuring and systematize the scientific disciplines which are the attributes and components of the theory and methodology of structuring. Figure 1 shows an example of such a systematization.

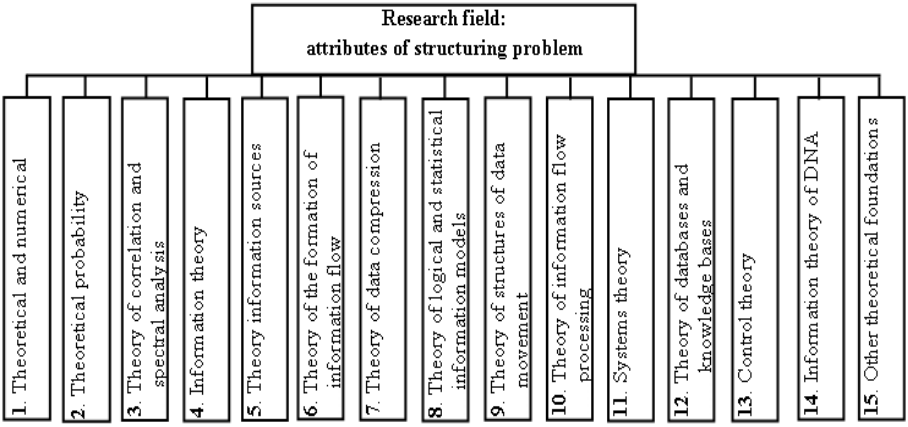


Figure 1. Structuring theory attributes classification.

Figure 2 shows generalized processes of information source flow structuring, where IS – information sources, S - sensory system, # - sampling processes in the Hamming space, FS - functional structuring, F(U, ∩) - operations of structural unification and separation.

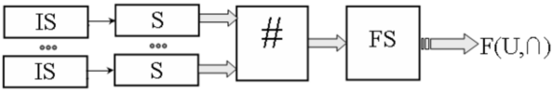


Figure 2. The process of structuring.

2.2. Generalization of Theoretical Bases and Functions of the Data Structuring Concept

A successful solution to the problem of structured data (SD) formulation and processing in the distributed computer systems is conceptually related to the appropriate use of a wide class of fundamental theoretical principles of computer science, cybernetics and systems engineering. It is necessary to formulate the basic attributes and information provision procedures of the generalized theory of data structuring [18].

Theoretical and applied bases of such a synthesis can significantly promote math development, improve transmission and processing of digital data and increase the efficiency of components and algorithm functions, and efectiveness of using processed data in distributed computer systems [2, 3, 5].

Different data type structuring and complex computer system modeling is an urgent task that aims at improving the theory, methodology, design practice and diagnosis of functioning in real time. In terms of methodology, solving this problem requires consideration of the problem orientation, integrity and complexity, uncertainty, adaptability and versatility of computer system. The level of purposefulness and the aim of the system functioning, the possibility of the system description using only one model, evaluation of entropy that reflects the required amount of control information, the possibility of the system adaptation to external factors, and the system description using mathematical models that have the same structure regardless of the volume of objects - sources are defined alongside.

Analysis of data structuring methods, substantiation of the theoretical perspectives, methodology and techniques of structuring in modern computer systems is an urgent task today.

Data structuring for executing the functions of generation, transmission, digital processing, storage and structured frame use to control objects is shown in Fig. 3.

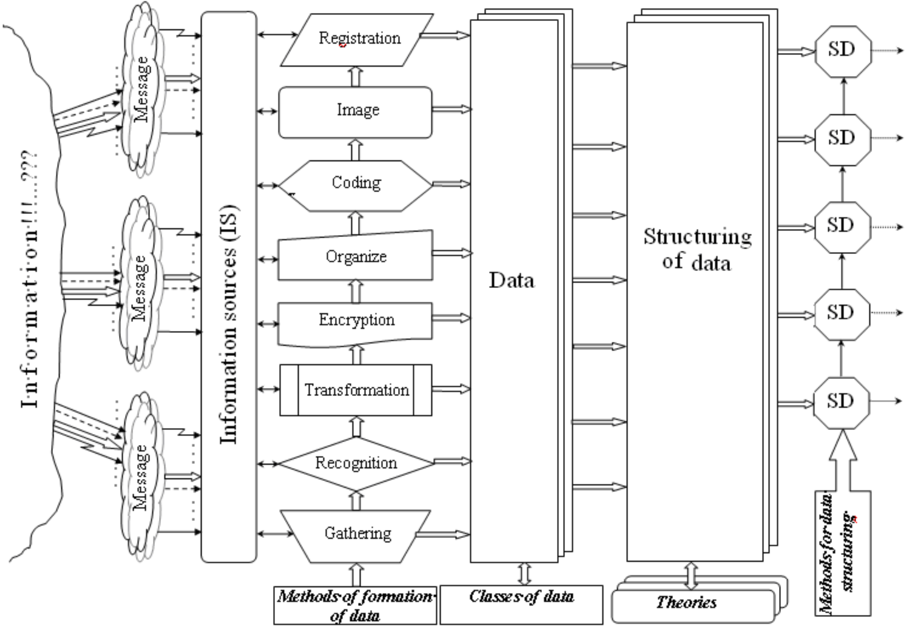


Figure 3. Generalized functions scheme of data structuring concept

Data structuring productive interaction functions scheme shows the way of data generation and algorithmic-mathematical data processing according to the task set, for example, pattern recognition, data compression, protection against unauthorized access, the results of the problem solved and others.

3. Investigating and Developing Criteria for Structural Complexity of Multifunctional Data

Synthesis and analysis of the DCS structures and components requires a clear definition of the system of criteria, on the basis of which, the comparison and optimization of the system characteristics of the developed software and hardware is carried out. The most common in modern practice of analyzing the system characteristics of computers, which are the components of DCS, are estimates of hardware and time complexity. In addition to the above, one more important criteria for assessing the perfection of the architecture of components, devices and MFD is the criterion of structural complexity.

Theoretical bases for estimating structural complexity were first proposed in the theory of graphs of Petri nets, which became the basis for calculating the structures of Petri nets [19]. Thus, effective application of theoretical bases of the estimate formalization of the structural complexity of the graphs representing Petri nets made it possible to systematize the ways of their structural representation, and also to formalize their functional transformations when pasting, differentiating, and presenting them in the form of trees, etc.

The result of the development of this direction of data structuring was the development of the theory and practical applications of the so-called "color" Petri nets, which are characterized by an extended functional description of the attributes of the network active nodes and edges. This made it possible to differentiate the attributes of the Petri net nodes such as information source, data processing and receiving points, data approval and use, which is shown in the research works of the author.

The functional transformations in the structure of Petri nets are performed according to adjacency (C_{ij}) and incidence (A_{ij}) matrices, which can be considered as initial estimates of structural complexity in DCSs that are represented by graphs of Petri nets:

$$C_{ij} = \begin{cases} V_j \rightarrow V_{j+1} = -1; \\ V_j \leftarrow V_{j+1} = +1, \end{cases} \qquad A_{ij} = V_i \,\&\, V_j \in \overline{0 \vee 1}.$$

The overall estimate of the structural complexity of Petri nets is determined by the ratio of the number of vertices (V_k) to the total number of one-directional (b_n) and bidirectional (b_m) edges:

$$k_c = \frac{V_k}{b_n + b_m},$$

where k, n, m - a number of vertices, a number of one-directional and bidirectional edges correspondingly.

The development of criteria for estimating the structural complexity of topologies and microelectronic components of computer operating devices is of great importance today. The first example of such an estimate is the Quine method [20] based on the estimate of the total number of inputs and outputs of the microelectronic structure, which is calculated according to the expression:

$$S_K = \sum_{i=1}^{n} X_i + \sum_{j=1}^{m} Y_j,$$

where X_i - inputs, $i \in \overline{1,n}$; Y_j - outputs, $j \in \overline{1,m}$;

n, m - the number of the structure inputs and outputs correspondingly.

The optimization criterion for the structure level according to Quine is determined by three criteria: the minimum number of logic gates in the structure, the minimum number of inputs and outputs in the structure, the minimum signal delay time. The last two criteria correspond to the estimates of hardware and time complexity of computing device structures.

The component of the criterion for estimating complexity according to Quine is the assessment of structural complexity by determining the hardware complexity of the device. This estimate is calculated determining the number of logic elements and gates in the structure of the devices with different numbers of hierarchies and types of components: single-level devices or components of different types - $A_{\Pi} = \sum_{i=1}^{n} A_i$

$A_{\Pi} = \sum_{j=1}^{m}\sum_{i=1}^{n} A_{ij}$, three-level devices $A_{\Pi} = \sum_{j=1}^{m}\sum_{i=1}^{n}\sum_{k=1}^{l} A_{ijk}$, where A_{Π} - the overall assessment of hardware complexity, i, j, k - types of components or levels of the structure of the device, m, n, l - the corresponding number of types of different components or levels of the device structure.

The functional limitations of this criterion lie in the fact that it does not take into account the topology of types, a number of relations and their intersections, crystal dimensions, a number of inputs and outputs, etc., which are important characteristics in microelectronic design of PLDs, FPGAs and nanotechnology tools.

M. V. Cherkaskyi proposed a criterion that to some extent solves this problem [21] based on the SH-model of the algorithm, which takes into account hardware in the explicit form:

$$B =< D, Q, g_0, g_f, G, P, M >,$$

where D – a finite set of characters of the external alphabet; Q – a finite set of states of SH-model; q_0 and q_f – initial and finite states: $q_0, q_f \in Q$; G – hardware configuration of the model: $G = (X, U)$; X – a set of elementary converters: $\{x_1, x_2, ..., x_n\}$; U – a set of connections: $\{u_1, u_2, ..., u_m\}$; P – program; M – memory.

The concept of "elementary converter" x_i, used in this model, is a unit of hardware complexity which converts a certain set of initial input data d_i into a set of output data d'_i: $x_i : \{d_i\} \rightarrow \{d'_i\}$.

When using the SH-model, such characteristics of complexity as hardware, time, capacity, software and structure are proposed to be used, where hardware complexity is the number of elementary converters and elements of RAM; time complexity is determined by the number of elementary converters in the maximum signal propagation path $L = |\max X_i|$; software complexity is determined by formula:

$$P = -F \log_2 \frac{F}{n \cdot m},$$

where $F = \sum_{L} f_l$; n – the number of control inputs; m – the number of time samples of the time chart; f_l – the number of control signals of the l-th fragment of the time chart; L – is the number of the time chart fragments, configurations of which are not repeated.

The structural complexity of the algorithmic device is determined by the following formula:

$$S = -E \log_2 \frac{E}{n(n-1)},$$

where E – the number of elements of the triangular adjacency matrix of the system; n – the number of vertices of the graph.

This criterion is used when estimating the structural complexity of operating devices and functional units of personal computers.

The functional limitation of such estimation lies in the fact that when calculating the structural complexity of homogeneous and regular environments $\log_2 = 1$ and differentiation of structural complexity becomes impossible.

The calculation of the structure time complexity is performed by determining the total number of micro-cycles of signal delay in the longest chain of series-connected logical or functional elements between the corresponding inputs and outputs of the device:

$$\tau = \sum_{j=1}^{m} \tau_j ,$$

where m - the number of series-connected elements; τ_j - signal delay in each j-th element.

In modern theory of binary and color digital image processing a wide range of mathematical expressions is used that makes it possible to classify, distinguish, recognize images by analyzing the structural complexity of components according to the appropriate algorithms and functionals.

The calculation of the structural complexity of the nodes of data movement matrix models based on the characteristics of emergence, proposed by J.Martin [1], corresponds to the ratio of the number of relations to the number of system components according to the estimate of the unit of data movement, and is as follows:

$$K_d = \frac{N_i}{N_0},$$

where N_i - the number of relations, N_0 - the number of components.

In [22], the symbolic attributes of Petri nets were expanded on the basis of data movement models (DMM), and the data movement coefficients, were taken into account:

$$K_{ed} = \frac{S_i \cdot G_0}{S_0 \cdot G_i},$$

where S_i, S_0, G_i, G_0 - the actual number of queries, the maximum possible number of queries, the actual number of records or updates, the maximum possible number of records or updates in the node of the matrix model respectively.

The structural complexity of microelectronic device topology, proposed by V.S.Glukhov [23], is estimated according to the total length of horizontal g_i and vertical v_i connections on the conventional FPGA:

$$L = \sum_{i=0}^{m-1} (g_i + v_i) \approx (1/2...3/4)m^2 \text{ , де } g_i = x_i + 1,\ v_j = m + d_i + 1$$

However, classification of the structure components with informative parameters and weight estimates of structural unit components were not included into the considered criteria.

We propose to estimate the structural complexity of circuit structures, graphic images and multifunctional data as follows [24,]:

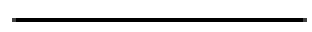
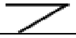
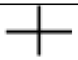
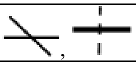
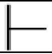
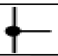
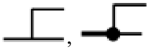
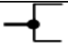
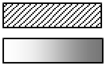
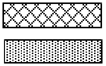
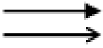
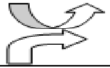
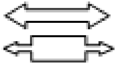
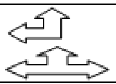
$$k_c = \sum_{i=1}^{n} \alpha_i P_i \ , \tag{1}$$

where $P_i \in (l, P, x, d, r, h, z, b, c, i, n, a, f)$ - informative parameters of structure attributes, α_i - weighting coefficients of expert estimates of structural complexity of structured data elements and components.

The proposed criterion, obtained on the basis of expert estimates, is one of the elements of building ontological models in the systems of intelligent data processing in organizational and technical complexes.

Table 1 shows symbol attributes of MFD structural components and expert estimates of the complexity coefficient α_i and the classified informative parameters $l, P, x, d, r, h, z, b, c, i, n, a$.

Table 1. Expert estimates of the structural complexity of MFD elements

№	Element designation identifier	The content of the element	Symbols	α_i	Symbols	α_i
1	l	Line		1		1,2
				1,5		1,2
				1,1		1,7
2	P	Turn		2		2,2
				2,2		
3	x	Intersection		3		3,1
4	d	Touch		2		2,2
5	r	Branching		4		6,2
6	h	Filling	 ,	2	 ,	2
7	z	Direction of a relationship		2		2,5
				3		3,4
				2,4		3,5
8	b	Letter	Aa…Яя, …, *Aa…Яя,*	8-10	Aa…Zz, …, *Aa...Zz Aa...Zz*	8-10
	c	Digit	1, 2,…0….	4	***1, 2,…0***	4
	i	Index	1, 2,…0, a, A	4	1, 2,…0, a, A	4
	s	Symbol	©, ®, π, ψ, ω, &, %,	4	☺, ☼ ♫, μ, $, *, €, ,	4
	n	Sign	+, -, <, >, =, ±, ≡, ≈..	2	≠, ≤, ≥, (, “, {, !, ?...	2

The proposed criterion for estimating structural complexity does not include the informative characteristics of the structure components, so MFD structure effectiveness criterion is proposed to determine the ratio between information and structural complexities according to the expression [24, 28, 29, 30]:

$$k_e = K \cdot \frac{F_C}{k_c} = K \cdot \frac{\sum_{j=1}^{m} f_j}{\sum_{i=1}^{n} \alpha_i P_i} \Rightarrow \max, \qquad (2)$$

where K – MFD level identifier ($K = n$,… – for n-level structures correspondingly); F_C - information complexity of the device; f_j - functional information characteristics of the device structure.

Thus, the maximum increase in k_e value is a comparative characteristic of different implementations of the device structures and MFD. For example, at a given structural complexity k_c , the functionality of the structures is expanded, or at a given functionality, structural complexity is reduced. This can lead to changes in target characteristics by reducing hardware, time or computational complexities.

Functional and informative characteristics of the device structure can be represented by the following estimates:

1. Functional completeness of the device inputs-outputs, which is determined by the total estimate $f_j = \sum_{i=1}^{n} \beta_i \cdot f_{input} + \sum_{i=1}^{m} \lambda_i \cdot f_{output}$, where f_j - functional information characteristics of the device structure, β, λ - coefficients of input-output functions informativity, m, n - the number of inputs-outputs, f_{input}, f_{output} - input-output functions (e.g., input / output channel, input / output x / y n / m -bit buses, synchronization input, crystal selection c / s , power supply $+ / -$);

2. The degree of availability of certain functions in the formalized structures of data movement derivative models. An example of the calculation is carried out according to the expression:

$$f_j = \sum_{j=1}^{m} f_i \,.$$

3. Evaluation of structural complexity based on entropy characteristics of input calculation and output information flows.

The entropy estimates are calculated according to coding (R. Hartley), probabilistic (K. Shannon) and correlation (Y.Nykolaychuk) information entropy measures [25-27]:

- R. Hartley: $H = n \cdot \hat{E}[\log_2 S] = n \cdot]\log_2 S[$;
- K. Shannon: $H = -k \sum_{j=0}^{S} p_j \log p_j$;
- Y. Nykolaychuk: $I_x = n \cdot \hat{\mathrm{E}}\left[\frac{1}{2} \log_2 \frac{1}{m} \times \sum_{j=1}^{m} \left(D_x^2 - R_{xx}^2(j) \right) \right]$,

where H – the amount of information; S – the number of independent equally probable states of the information source (IS); n – the number of samples; $\hat{E}[\bullet]$ – an integer-valued function with rounding to a larger whole; k – a positive coefficient that takes into account the base of the logarithm; p_j – the probability of the S_j-th state of the discrete IS; S – the number of independent IS states; $\overset{\circ}{x}_i = x_i - M_x$ – centered values of the data array; $D_x = \frac{1}{n}\sum_{i=1}^{n}(x_i - M_x)^2$ – dispersion x_i; $M_x = \frac{1}{n}\sum_{i=1}^{n} x_i$ – mathematical expectation; $R_{xx}(j) = \frac{1}{n}\sum_{i=1}^{n} \overset{\circ}{x}_i \cdot \overset{\circ}{x}_{i+j}$ – autocorrelation function (ACF); m – the number of points of the function $R_{xx}(j)$ on the correlation interval; $j = 0,1,....m$.

Thus, the estimation of the entropy functional complexity looks as follows:

$$f_j = I_{input} + I_X + I_{output},$$

where $I_{input}, I_X, I_{output}$ - quantification of entropy at the input, during the transformation and at the output of the structure, respectively.

Based on the proposed criterion (1), a method for estimating the structural complexity of the attributes of multi-level DCS data movement models, as well as alphanumeric and functional symbols, which are displayed on monitors and hard copies of physical data, is developed [24].

4. Examples of Estimating the Structural Complexity of Elementary Units of Computer Technology

The above systematization of structural elements formed the basis of the methodology for estimating the structural complexity of logical elements and structures of microelectronic devices in computer technology.

The logical element is the most elementary component in computer technology. Therefore, the estimation of the structural complexity of any component of DCSs (ADC, adders, multipliers, entropy measurement devices, processors, special-purpose processors, memory, etc.) is based on determining the structural complexity of the logical elements, taking into account the relationships between them.

Based on the criterion (1) and the data in Table 1, the structural complexity of the microelectronic components of the processors is estimated (Table 2).

The following tables show examples of estimating the structural complexity and informativity of various graphic images in electrical automatics, and crystals of logical and microelectronic components.

Table 2. Informative characteristics of the logical element structural complexity of computer technology.

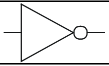
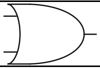
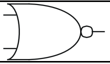
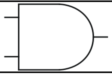
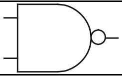
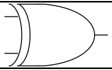
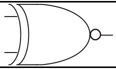
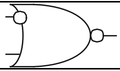
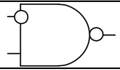
№	Function, type of a component	Symbolic graphic notation	Criterion parameters for structural complexity l,P,x,d,r,h,z,b,c,i,n	Total estimate of structural complexity
1	Denial		2,3,-,3,-,-.-,-,-,-,-	14,8
2	Disjunction		1,2,-,3,-,-,-,-,-,-.-	11,6
3	Denial of disjunction		2,2,-,4,-,-,-,-,-,-,-	14,8
4	Conjunction		1,2,-,3,-,-,-,-,-,-,-	11,2
5	Denial of conjunction		2,2,-,4,-,-,-,-,-,-,-	14,4
6	Equivalency		2,2,-,3,-,-,-,-,-,-,-	12,8
7	Denial of equivalency		3,2,-,4,-,-,-,-,-,-,-	16
8	Implication		3,2,-,6,-,-,-,-,-,-	20
9	Prohibition		3,2,-,6,-,-,-,-,-,-	19,6

Table 3. Symbolic notation of graphic images in electrical automatics

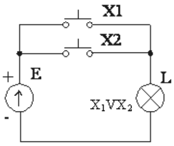
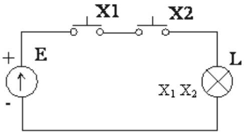
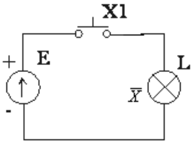
№	Function, type of a component	Symbolic graphic notation	Total estimate of structural complexity
1	Disjunction		130
2	Conjunction		111
3	Denial		70

Table 4. Nonlinear diode transistor elements

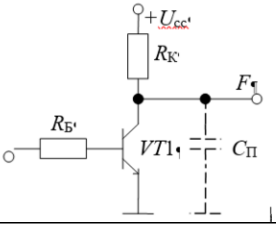
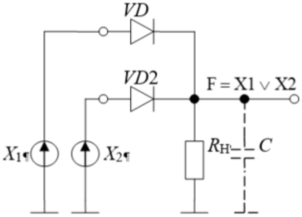
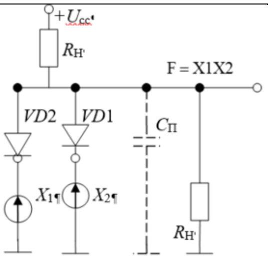
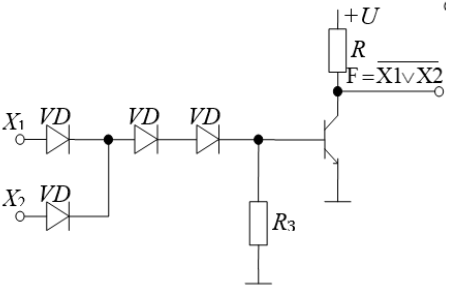
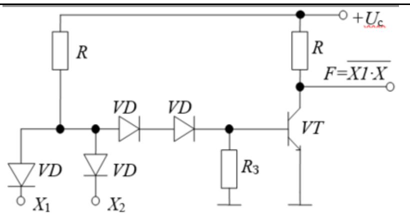
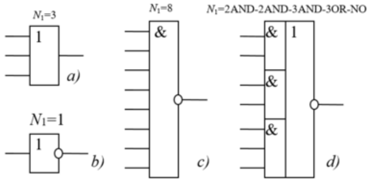
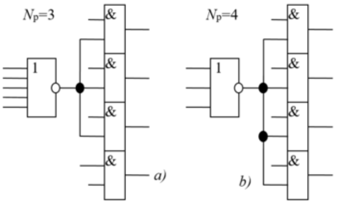
№	Function, type of a component	Symbolic graphic notation	Total estimate of structural complexity
1	Element NO		180
2	Element OR		251
3	Element AND		315
4	Element OR-NO		368
5	Element AND-NO		393

Table 5. Symbolic notation of logical element crystals

№	Function, type of a component	Symbolic graphic notation	Total estimate of structural complexity
1	Examples of coefficient N_l values		a) – 28 b) – 23 c) – 42 d) – 74
2	Majority elements		a) – 177 b) – 232

An example of a multi-bit arithmetic processor component is a modified pseudo-random code sequence delimited feedback register (Fig. 4).

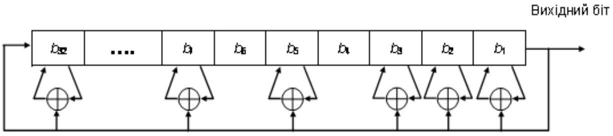


Figure 4. Modified feedback register

$$k_e = {k_i}/{n} + k_{e2} + k_{e3} = {96}/{n} + 3 + 17,$$

n - the number of regular elements, when $n = 1024$ $k_e \approx 21$

Possibility of structuring information and transition from one structure to another provides a basis for efficient analysis and evaluation, processing and regrouping.

5. Conclusions

Based on the analysis of modern theories and tools of formation, conversion, transmission and digital processing of information flows in complex CSs, the concept of structuring multifunctional analog and digital data processing is proposed, which makes it possible to improve the processes of synthesized generation and movement of structured data and implement computing tools with advanced functionality and reduced structural, hardware and time complexities.

The proposed criteria of structural complexity as a weighted sum of structural characteristics and the informative characteristics of multifunctional data structures, allow us to compare and improve the system characteristics (structural, hardware and time complexities) of the software and hardware being created, which form multifunctional data.

Since the method for assessing the structural data complexity is proposed for the first time, it is considered as a new one and needs further development and improvement.

Today, it is still hard to say exactly how perfect it is, and it is also difficult to compare it with any other method. Therefore, the development of the theory of structuring multifunctional data needs further elaboration, which will be discussed in our future research papers.

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