Розроблено метод оцінки складності структури технологічних систем, який базується на використанні критерію, що враховує число елементів системи та зв'язків між елементами, зв'язків між елементами та зовнішнім середовищем, а також ієрархічний рівень елементів. Застосування на практиці розробленого методу дозволяє вирішити задачу об'єктивного аналізу структури технологічних систем і дати кількісну оцінку їх складності. Наведено приклад використання критерію і методу для аналізу структури систем технологічного обладнання агломераційних фабрик Криворізького залізорудного басейну (Україна)

Ключові слова: технологічні системи та елементи, структура технологічних систем, критерій складності структури технологічних систем

Разработан метод оценки сложности структуры технологических систем, который базируется на использовании критерия, учитывающего число элементов системы и связей между элементами, связей между элементами и внешней средой, а также иерархический уровень элементов. Применение на практике разработанного метода позволяет решить задачу объективного анализа структуры технологических систем и дать количественную оценку их сложности. Приведен пример использования критерия и метода для анализа структуры систем технологического оборудования агломерационных фабрик Криворожского железорудного бассейна (Украина)

Ключевые слова: технологические системы и элементы, структура технологических систем, критерий сложности структуры технологических систем

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DEVELOPMENT OF THE CRITERION AND THE METHOD OF ESTIMATION OF THE COMPLEXITY OF THE STRUCTURE OF TECHNOLOGICAL SYSTEMS

Yu. Rud
Doctor of Technical Sciences, Professor,
Head of Department*
E-mail: rudusprof@gmail.com
V. Belonozhko
Senior Lecturer*
E-mail: v.u.belonozhko@gmail.com
*Department of Applied Mechanics
and General Engineering Disciplines
Kryvyi Rih National University
Vitaliya Matusevycha str., 11,
Kryvyi Rih, Ukraine, 50027

1. Introduction

Technological systems of modern industrial enterprises belong to the class of complex ones and are intended for the transformation of matter, energy, information in the process of production, materials processing, assembly of finished products, quality control [1]. In [2], it is noted that technological approaches, based on technology, are a means of increasing the productivity of an enterprise. A complex technological system consists of many interacting subsystems (parts of systems), whereby it acquires new properties that are absent at the level of subsystems [3–6]. In system studies [7–9], the concept of «complex system» is used when it becomes impossible or difficult enough to accurately describe and predict the behavior of the system. One of the first definitions of a complex system was given in [10, 11], where it was noted that the important properties of complex systems are the possibility of dividing the system into subsystems, as well as the existence of a hierarchical structure. In the practice of research, the allocation of subsystems is carried out in such a way that the goals of the operation of subsystems ensure the possibility of realizing the goals of the functioning of the system as a whole. The components of subsystems are the equipment that implements the technological processes that ensure the transformation of the physical and mechanical properties of the processed product. The result of the functioning of technological subsystems is an intermediate or final product, which requires further processing at other industrial enterprises. A certain technology can be implemented using equipment of different manufacturers and productivity, which leads to the creation of subsystems with a structure of different hierarchical levels. Accordingly, the reliability, efficiency and cost of such systems will also be different and may vary significantly. Therefore, when designing and manufacturing complex technological systems, it is necessary to have the means and criteria for assessing the perfection of their structure.

2. Literature review and problem statement

The structure of the technological system is its most essential components and connections, which change little with time and ensure the stable existence of the system and the preservation of its basic properties [12]. The main characteristic of the structure of the technological system is its complexity [13]. The concept of complexity of a finite object was introduced in the paper and is based on a key theorem, first discovered and described in [15–17]. Complexity is the minimum number of binary digits that contains all information about a given object, sufficient for its recovery (decoding). The first consequence of the key theorem is that there is no effective way of complexity computation, so the practical application of this criterion of complexity is difficult. For schemes of functional elements realizing the functions of the algebra of logic, an asymptotic equality is proposed that makes it possible to estimate the complexity of the object $L(n)$ using the criterion [18]

$$L(n) \approx c2^n/n, \tag{1}$$

where n is the number of variables x_1, x_2, x_3,..., x_n; c is the constant depending on the basis.

It should be noted that methods of logic algebra are applicable to elements that have only two possible states, when the condition of working capacity can be expressed as a Boolean function. In addition, the definition of complexity by equation (1) depends essentially on the decoding method, and the measure of complexity is not a computable function [19].

In fact, by the complexity of the structure, the authors of many works mean only the number or state of the elements contained in the system [20, 21]. However, technological systems are characterized not only by a large number of elements (equipment), but also by the complexity of the internal structure – various kinds of redundancies, direct and reverse connections, and so on. Therefore, the number of elements that complete the system cannot serve as a measure of complexity of the structure of technological systems. The complexity of the internal structure leads to the appearance of a new system quality, depending both on the number of elements and on the relationships between them. This approach to the complexity of the structure is carried out in the general systems theory [22, 23], as well as in a number of modern scientific publications.

In [24], a model and indices for estimating the structural complexity of the layout of production systems are presented. Six complexity indices are introduced and formulated based on the physical structural characteristics of the layout. The overall complexity index of the layout combines all the indices. The proposed model and indices are applicable for assessing the structural complexity of the layout of a production facility, but not a real technological system. It is noted in [25, 26] that the variety of products and the growing requirements for the flexibility of the system increase the complexity of the structure. An approach based on operations for measuring the complexity of the configuration of the production system is proposed. It is proposed to measure the complexity of the configuration of the production system using information entropy. This approach is of some interest, but it is difficult for practical application. The authors of [27] note that complexity reduction is an effective way to improve the reliability of production systems. Nevertheless, studies on complexity analysis based on reliability for production systems are rare. In [28], it is stated that with increasing product complexity, traditional methods of reliability design do not contribute to the realization of high reliability requirements. To build a structure with high reliability became a problem that requires an urgent solution. It is proposed to use the theory of axiomatic design to solve problems of reliability design. In [29], the problem of reliability optimization and the problem of reliability redundancy distribution are considered. To maximize the reliability of systems, a strategy is proposed to change their structure by using active or standby redundancy for each subsystem. The authors of [30] emphasize that technical systems are complex, endowed with sets of properties and functions, and require constant monitoring of their condition. There is an opportunity to assess the state of the technical system and its structure through a measure of the uncertainty of information entropy. However, because of the variety of system states, it is impossible to apply any known methods for determining the amount of entropy.

The authors of [31] write: «It seems that the concept of complexity for a control theory is as fundamental as the concept of «force» in mechanics or «measure» in mathematics». However, only the author of [32] presented a method and a criterion for estimating the complexity of a structure, which makes it possible to obtain a quantitative estimate of this parameter:

$$S = (1+\nu\alpha)\sum_{i=1}^{n} S_i k_i, \tag{2}$$

where ν is the coefficient that takes into account the complexity of the connections in comparison with the complexity of system elements; α is the coefficient characterizing the number of realized connections; S_i is the complexity of system elements; k_i is the number of elements of the i-th type included in the system.

With all the validity and reliability of the mathematical expression (2), its practical application to real technological systems is difficult in connection with the significant subjectivity of determining the coefficients that take into account the complexity of the connections ν and elements of the system S_i.

Thus, the development of a criterion and a method for assessing the complexity of the structure of technological systems, which will enable reliable and objective quantification, is of theoretical and practical interest. This is especially important for technological systems when considering them from the standpoint of system engineering. Accounting for the complexity of the structure provides a qualitatively new approach to investigating the problem of reliability and increasing the productivity and efficiency of technological systems.

3. The aim and objectives of the study

The aim of the work is to develop a method for an objective assessment of the perfection of the structure of technological systems using a quantitative criterion.

To achieve the aim, the following objectives are set:

– in well-known studies on the problem of evaluating the structure of complex systems of different functional purposes, to find rational elements of solutions suitable for use in technological systems;

– to develop a criterion and a method for quantifying the structure of complex technological systems that are sufficiently accurate, intuitively acceptable and suitable for practical research;

– to carry out approbation of the developed criterion and method on the example of systems of technological equipment of sintering plants of the Krivoy Rog basin (Ukraine).

4. Development of a criterion and method for assessing the complexity of the structure of technological systems

The criterion for quantitative estimation of the complexity of the structure of technological systems is fulfilled under the following initial assumptions [13].

1. The element of the system has one «input» and one «output», through which it interacts with other elements of the system or the external environment (Fig. 1, *a*). «Input» refers to the channel through which the preceding element of the system or the external environment acts on this element, changing its state. «Output» refers to the channel through which this element affects the subsequent element of the system or the external environment, by changing their states. In Fig. 1, «input» and «output» of elements and systems are shown by a short horizontal line.

2. The state of the system element is uniquely determined by the state of its «input».

3. The complexity of the structure of the unit element $S(n)$ is one, that is, $S(n=1)=1$.

4. The complexity of the structure of the system consisting of an infinite number of elements $S(n)$ is infinite, that is, $S(n=\infty)=\infty$.

5. The complexity of the structure of the system $S(n)$ is determined by the number of elements of the system n, the number of connections between them and the external environment m, and also by the hierarchical level of the element in the system I.

Logical realization of the initial assumptions 1–5 makes it possible to describe the criterion for the complexity of the structure of the system $S(n)$ consisting of n elements by the following mathematical expression:

$$S(n)=(m-1)nI, \tag{3}$$

where n is the number of system elements; m is the number of connections between elements, as well as elements and the external environment; I is the hierarchical level of elements in the system.

Applying the mathematical expression (3), we calculate the index of complexity of the system $S(n)$ consisting of n consecutively connected elements [3], for $n=1$, $m=2$, $I=1$ (Fig. 1).

$$S(n=1)=(2-1)\cdot 1\cdot 1=1. \tag{4}$$

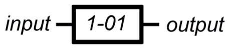

Fig. 1. Symbol of a system element

We continue the calculation of the complexity index of the system $S(n)$ with increasing number of elements $n=2, 3, \ldots,$ connected in series, with $m=3, 4, \ldots$ (Fig. 2, 3). The mathematical expression for determining the index of complexity of the system $S(n)$, consisting of n consecutively connected elements, is as follows:

$$S(n)=n^2 I. \tag{5}$$

Fig. 2. Series connection of system elements, $n=2$

The hierarchical level I of the element in the system of a simple structure consisting of n consecutively connected elements 1-01 and 1-02 (the first digit is the number of the branch of the structure, the second digit is the element number) is equal to one, i. e. $I=1$.

Applying the mathematical expression (5), we calculate the index of complexity of the system $S(n)$ consisting of n consecutively connected elements, for $n=\infty$, $m=\infty$, $I=1$ (Fig. 3).

$$S(n=\infty)=\infty^2\cdot 1=\infty. \tag{6}$$

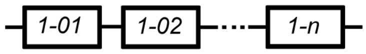

Fig. 3. Series connection of system elements, $n=2,\ldots,\infty$

We continue the calculation of the complexity index of the system $S(n)$ with a further increase in the number of elements $n=3, 4, \ldots$ connected in parallel, and $m=6, 7, \ldots$ (Fig. 4). The mathematical expression for determining the complexity index of the system $S(n)$ consisting of n parallel-connected elements is as follows:

$$S(n)=(2n-1)nI. \tag{8}$$

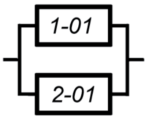

Fig. 4. Parallel connection of system elements, $n=2$

Applying the mathematical expression (8), we calculate the complexity index of the system $S(n)$ consisting of n parallel connected elements, for $n=\infty$, $m=\infty$, $I=1$ (Fig. 5).

$$S(n=\infty)=(2\infty-1)\cdot\infty\cdot 1=\infty. \tag{9}$$

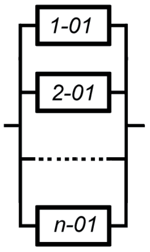

Fig. 5. Parallel connection of system elements, $n=2,\ldots,\infty$

Consider several systems that have more complex structures, which consist of n elements with a combined serial and parallel connection and form separate subsystems. Subsystems, as part of the system, are included in it in series. In [33], it is noted that many researchers of the problem of reliability optimization consider the best structure using elemental redundancy – a series-parallel structure.

Fig. 6 shows a system consisting of two subsystems: one subsystem consists of one element 1-01, the other subsystem – of two parallel elements 2-02 and 3-02. The hierarchical level I of the subsystems obtained by the first division of the system is two, that is, $I=2$. The first division of these subsystems (the second division of the system) provides a hierarchical level

$I=3$, etc. According to the mathematical expression (3), the complexity of the system $S(n)$ for $n=3$, $m=5$, $I=2$:

$$S(n=3)=(5-1)\cdot 3\cdot 2=24. \tag{10}$$

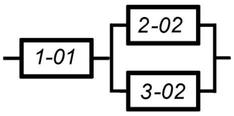

Fig. 6. Combined series-parallel connection of system elements, $n=3$

We complicate the system shown in Fig. 6, by introducing another element connected in series into the first subsystem. We obtain the following characteristics: $n=4$, $m=6$, $I=2$:

$$S(n=4)=(6-1)\cdot 4\cdot 2=40. \tag{11}$$

Changing the location of an element in the system does not change the number of connections, since the elements are structurally connected in the system, regardless of their position on the diagram.

Let's increase the number of elements to $n=5$ and build two subsystems on their basis: the 1st subsystem – element 1-01; the 2nd subsystem – element 2-02, connected in parallel with the elements 3-02, 4-02 (connected in parallel) and the element 5-01 connected in series (Fig. 7). At the same time, the number of connections will increase to $m=8$, the hierarchical level of the system will not change $I=2$. Calculation of the system characteristics by the formula (3) gives such results:

$$S(n=5)=(8-1)\cdot 5\cdot 2=70. \tag{12}$$

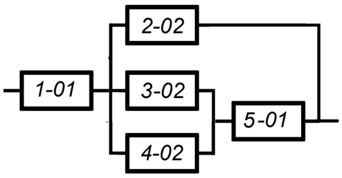

Fig. 7. Combined series-parallel connection of system elements, $n=5$

Let us change the structure of the subsystems of the system without changing the number of elements $n=5$: the 1st subsystem is the element 1-01; the 2nd subsystem consists of four parallel-connected elements. In this case, the number of connections will increase to $m=9$, the hierarchical level of the system will not change $I=2$.

$$S(n=5)=(9-1)\cdot 5\cdot 2=80. \tag{13}$$

From the analysis of the results of solutions (12) and (13), we can draw the following conclusion: in order to maximize the complexity of the structure of the system, it is first necessary to increase the number of parallel circuits.

The results of calculation of the complexity indices of systems $S(n)$ consisting of n series, parallel and combined connected elements are given in Table 1.

As the structure of the system becomes more complicated due to the increase in the number of elements and the creation of new connections, its functional capabilities are expanded. At the same time, the number of types of technological operations performed by individual subsystems grows, additional reserve connections between the elements are created. As a result, the reliability of the system and the stability of its functioning in the event of interference increase.

Table 1

The results of calculating the complexity indices of systems $S(n)$ consisting of n series and parallel connected elements

Amount of elements in the system n	Amount of connections between the elements and the external environment m	Hierarchical level of the element in the system I	Calculation of the complexity indicator of the system $S(n)$	Notes
		Series connection of elements		
1	2	1	$S(n=1)=(2-1)\cdot1\cdot1=1$	Fig. 1
2	3	1	$S(n=2)=(3-1)\cdot2\cdot1=4$	Fig. 2
3	4	1	$S(n=3)=(4-1)\cdot3\cdot1=9$	Fig. 3
4	5	1	$S(n=4)=(5-1)\cdot4\cdot1=16$	Fig. 3
5	6	1	$S(n=5)=(6-1)\cdot5\cdot1=25$	Fig. 3
6	7	1	$S(n=6)=(7-1)\cdot6\cdot1=36$	Fig. 3
7	8	1	$S(n=7)=(8-1)\cdot7\cdot1=49$	Fig. 3
...	...	....	...	...
∞	∞	1	$S(n=\infty)=(\infty-1)\cdot\infty\cdot1=\infty$	Fig. 3
		Parallel connection of elements		
2	4	1	$S(n=2)=(4-1)\cdot2\cdot1=6$	Fig. 4
3	6	1	$S(n=3)=(6-1)\cdot3\cdot1=15$	Fig. 5
4	8	1	$S(n=4)=(8-1)\cdot4\cdot1=28$	Fig. 5
5	10	1	$S(n=5)=(10-1)\cdot5\cdot1=45$	Fig. 5
6	12	1	$S(n=6)=(12-1)\cdot6\cdot1=66$	Fig. 5
7	14	1	$S(n=7)=(14-1)\cdot7\cdot1=91$	Fig. 5
...	...	...	...	...
∞	∞	1	$S(n=\infty)=(\infty-1)\cdot\infty\cdot1=\infty$	Fig. 5
		Combined series and parallel connection of elements		
3	5	2	$S(n=3)=(5-1)\cdot3\cdot2=24$	Fig. 6
4	6	2	$S(n=4)=(6-1)\cdot4\cdot2=40$	–
4	6	2	$S(n=4)=(7-1)\cdot4\cdot2=48^*$	–
5	8	2	$S(n=5)=(8-1)\cdot5\cdot2=70$	–
5	9	2	$S(n=5)=(9-1)\cdot5\cdot2=80^*$	Fig. 7
6	11	2	$S(n=5)=(11-1)\cdot6\cdot2=120^*$	–

*Note: * – complex combination of elements*

5. Development of a criterion and a method for assessing the relative complexity of the structure of technological systems

Comparison of the complexity indices of the structure of systems $S(n)$ consisting of different numbers of elements n and having different numbers of connections between elements and the external environment m, as well as different hierarchical levels of the element of the subsystem I, is rather complicated. At the same time, it is possible to avoid reservations on the listed parameters, and complex quantitative indicators cannot be obtained due to the absence of a criterion. To solve this problem, it is proposed to use the criterion of relative complexity $s(n)$, which is determined from the following mathematical expression:

$$s(n)=S(n)/S_{\max}(n), \tag{14}$$

where $S(n)$ is the indicator of the complexity of the structure of the projected or operating system; $S_{\max}(n)$ is the maximum possible value of the complexity indicator of the structure of the system, constructed of n elements.

Analysis of the data of Table 1 shows that for the maximum possible value of the index of relative complexity of the structure $S_{\max}(n)$ of the system built of n elements, we can take the value of the complexity index of the structure of the system with the combined connection of elements $S_{\text{combin}}(n)$. Therefore, we accept for systems of equal hierarchical level:

$$S_{\max}(n)=S_{\text{combin}}(n). \tag{15}$$

The results of calculating the indicators of relative complexity $s(n)$ of systems of one hierarchical level, consisting of n series and parallel connected elements, are given in Table 2.

Table 2

The results of calculating the relative complexity indices $s(n)$ of systems consisting of n series and parallel connected elements

Amount of elements in the system n	Amount of connections between the elements and the external environment m	Hierarchical level of the element in the system I	Calculation of the complexity indicator of the system $S(n)$	Notes
Series connection of elements				
1	2	1	$s(n=1)=1/1=1$	Fig. 1
2	3	1	$s(n=2)=4/6=0.667$	Fig. 2
3	4	1	$s(n=3)=9/15=0.6$	Fig. 3
4	5	1	$s(n=4)=16/28=0.571$	Fig. 3
5	6	1	$s(n=5)=25/45=0.556$	Fig. 3
6	7	1	$s(n=6)=36/66=0.545$	Fig. 3
7	8	1	$s(n=7)=49/91=0.538$	Fig. 3
...	...	...	...	...
∞	∞	1	$s(n=\infty)=0.5$	Fig. 3
Parallel connection of elements				
2	4	1	$s(n=2)=6/6=1$	Fig. 4
3	6	1	$s(n=3)=15/15=1$	Fig. 5
4	8	1	$s(n=4)=28/28=1$	Fig. 5
5	10	1	$s(n=5)=43/43=1$	Fig. 5
6	12	1	$s(n=6)=66/66=1$	Fig. 5
7	14	1	$s(n=7)=91/91=1$	Fig. 5
...	...	...	...	...
∞	∞	1	$s(n=\infty)=0.5$	Fig. 5
Parallel connection of elements by the equation with respect to combined connection				
3	5	2	$s(n=3)=15/24=0.625$	Fig. 6
4	6	2	$s(n=4)=28/40=0.7$	–
4	6	2	$s(n=4)=28/48=0.583$*	–
5	8	2	$s(n=5)=43/70=0.614$	–
5	9	2	$s(n=5)=43/80=0.538$*	Fig. 7
6	11	2	$s(n=6)=66/120=0.550$*	–
...	...	...	...	...
∞	∞	2	$s(n=\infty)=0.5$	–

*Note: * – complex combination of elements*

Limit values of the indicator of relative complexity $s(n)$ with increasing the number of elements up to $n\to\infty$ are found as:

$$\lim_{n\to\infty} s(n)=\lim_{n\to\infty}\frac{S_{ser}(n)}{S_{par}(n)}=\lim_{n\to\infty}\frac{n^2 I}{(2n-1)nI}=$$

$$=\lim_{n\to\infty}\frac{n}{2n-1}=0.5. \tag{16}$$

The indicator of relative complexity $s(n)$ characterizes the perfection of the structure of the system, shows the degree of rationality in the use of elements in the structure.

6. Discussion of research results and practical use of the criterion and method for assessing the complexity of the structure of technological equipment systems

Accounting for the complexity of the structure can provide a qualitatively new approach to the study of the problem of reliability and improving the efficiency of technological systems. Intuitively, the structure of technological systems is often associated with their reliability. One of the most important ways to improve the reliability of systems is to change their structure by reserving separate elements and subsystems. However, the introduction of structural redundancy in the system is difficult and expensive, which limits such redundancy. A final decision on the feasibility and level of structural redundancy of individual subsystems is possible when using the developed method for assessing the complexity of the structure of technological systems. The proposed method provides a quantitative assessment of the complexity of the structure of technological systems, shows the degree of perfection of their structure, the rationality of using elements in the system.

From the point of view of practical application, the results of the assessment of the complexity of the structure of systems of technological equipment (STE) of sintering plants in the Krivoy Rog iron ore basin can be indicative:

– Novo-Krivoy Rog mining and processing plant before and after reconstruction – NKMPP-1, 2 and NKMPP-1-2R;

– Southern mining and processing plant – SMPP-1, 2;

– Krivoy Rog metallurgical plant (KMP-1), performed according to the proposed method (Table 3).

The absolute values of the complexity index $S(n)$ are given in the numerator, relative values of the complexity index $s(n)\cdot 10^{-3}$ [3, 13, 34] are given in the denominator. If the considered main subsystem contains subsystems of the first hierarchical level, then the complexity indicators $S_j(n)$ are given in parentheses in the order of the complexity evaluation.

A comparative analysis of the complexity indicators of the STE of sintering plants (Table 3) shows that after the reconstruction of the NKMPP-2P, its technological system became one of the most complicated. The number of basic elements of this system increased by 27.5 % (from 136 to 186), and the indicator of complexity of the structure reached the value $S(186)=370$.

Table 3

Indicators of complexity of the structure of STE of sintering plants

Company	Absolute and relative complexity indicators of subsystems $S(n)/s(n)\cdot 10^{-3}$	Absolute and relative complexity indicators of STE $S(n)/s(n)\cdot 10^{-3}$
NKMPP-1	SS-1: 28/269.2 (7/259.3); SS-2: 240/33.1 (20/95.7); SS-3: 8/888.9 (2/1000); SS-4: 32/237.1 (4/444)	308/25.81
NKMPP-2	SS-1: 28/269.2 (7/259.3); SS-2: 240/33.1 (20/95.7); SS-3: 8/888.9 (2/1000)	276/28.78
NKMPP-2R	SS-1: 28/269.2 (7/259.3); SS-2: 300/26.5 (25/77.2); SS-3: 8/800 (2/1000); SS-4: 16/457.1 (4/444); SS-5: 2/1000 (1/1000); SS-6: 16/457.1 (4/444.4)	370/21.26
SMPP-1, 2	SS-1: 28/269.2 (7/259.3); SS-2: 200/39.6 (20/95.7); SS-3: 2/1000 (1/1000)	230/33.90
KMP-1	SS-1: 24/311.7 (6/300); SS-2: 240/33.1 (20/95.7); SS-3: 8/888.9 (2/1000)	272/29.20

The number of connections between the elements of the STE of the sintering plant NKMPP-2R increased. At the same time, the relative indicator of the complexity of the $s(n)$ system structure not only did not increase, but even decreased by 35.2 %. The number of elements of the STE of the sintering plant NKMPP-2R, in comparison with the systems of sintering plants NKMPP-1, SMPP-1, 2, KMP-1, respectively, is more by 17.2 %, 37.6 %, 26.9 %. The relative complexity of the structure $s(n)$ of these factories is lower by 21.3 %, 59.3 %, 37.2 %, respectively.

Fig. 8 shows the graphs of the relative complexity of the structure $s(n)\cdot 10^{-3}$ of the systems of technological equipment of sintering plants and pelletizing plants of ore mining and processing plants depending on the number of elements n constructed from the results of research.

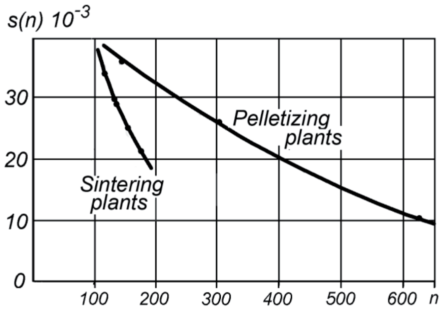

Fig. 8. Graphs of the relative complexity of the structure $s(n)\cdot 10^{-3}$ of systems of technological equipment of sintering plants and pelletizing plants of ore mining and processing plants depending on the number of elements n

As can be seen from Fig. 8, the indicator of the relative complexity of the structure $s(n)\cdot 10^{-3}$ decreases rapidly with increasing number of elements n of the system. The decrease in the relative complexity index of the structure of systems $s(n)$ with a large number of elements n is explained by the fact that the complexity of real systems grows considerably more slowly than the number of constituent components of n. A hierarchical level of elements is of great importance for the value of the indicator of the relative complexity of the structure $s(n)\cdot 10^{-3}$. And in real technological systems, the complexity of the structure is mainly due to the sequential inclusion of additional equipment, which cannot be considered rational.

7. Conclusions

1. A method for assessing the complexity of the structure of technological systems by the criterion that is a complex quantity and takes into account the number of system elements connections between the elements, connections between elements and the external environment, and the hierarchical level of elements in the system is developed. The method allows obtaining a reliable and objective quantitative assessment of the complexity of the system structure, is intuitively acceptable and suitable for practical research.

2. The indicator of the relative complexity of the structure of technological systems is proposed, which is the ratio of the indicator of the complexity of the structure of the projected or operating system to the indicator of the complexity of the structure in a combined connection of elements, characterizes the perfection of the system structure, shows the degree of rationality in the use of elements in the structure. The use of the indicator of the relative complexity of the structure ensures validity and correctness when comparing technological systems consisting of different numbers of

elements having different numbers of connections between elements and the external environment, as well as different hierarchical levels of elements.

3. Approbation of the developed method on the example of systems of technological equipment of sintering plants of the Krivoy Rog iron ore basin (Ukraine) was carried out. It is shown that in real technological systems, the complexity of the structure is mainly due to sequential inclusions of additional equipment, which cannot be considered rational. To increase the relative complexity of the structure of technological systems, we can recommend the use of combined series-parallel inclusion of additional process equipment, which ensures a high hierarchical level of elements in the system.

References

1. Economic Dictionary [Electronic resource]. – Available at: http://ekslovar.ru/
2. Mourtzis, D. Design and Planning of Manufacturing Networks for Mass Customisation and Personalisation: Challenges and Outlook [Text] / D. Mourtzis, M. Doukas // Procedia CIRP. – 2014. – Vol. 19. – P. 1–13. doi: 10.1016/j.procir.2014.05.004
3. Rud, Yu. S. Reliability and efficiency of equipment of agglomeration factories [Text] / Yu. S. Rud. – Moscow: Nedra, 1977. – 200 p.
4. Hall, A. D. Definition of System [Text] / A. D. Hall, R. E. Fagen // General Systems. – 1956. – Vol. 1. – P. 18–28.
5. Hubka, V. Theorie der Maschinensysteme (Theory of Machine Systems) [Text] / V. Hubka. – Berlin Heidelberg: Springer-Verlag, 1974.
6. Mesarovich, M. D. General Systems Theory [Text] / M. D. Mesarovich, Y. Takahara // Mathematical Foundations. – New York, San Francisco, London, 1975. – 268 p.
7. Hall, A. D. A Methodology for Systems Engineering [Text] / A. D. Hall. – Van Nostrand, 1962. – 478 p.
8. Bertalanffy, L. General System theory. Foundations, Development, Applications [Text] / L. Bertalanffy. – 1-st ed. – New York: George Braziller, lnc., 1968. – 289 p.
9. Asprey, W. Conquer System Complexity [Text] / W. Asprey et. al. // Build Systems with Billions of Parts, in CRA Conference on Grand Research Challenges in Computer Science and Engineering. – Warrenton, VA, 2002. – P. 29–33.
10. Buslenko, N. P. On the formal description of connections between elements of a complex system [Text] / N. P. Buslenko // Cybernetics. – 1972. – Issue 6. – P. 45–53.
11. Buslenko, N. P. Lectures on the theory of complex systems [Text] / N. P. Buslenko, I. N. Kalashnikov, V. V. Kovalenko. – Leningrad: Sovetskoe radio, 1973. – 440 p.
12. Mesarovich, M. Theory of Hierarchical Multilevel Systems [Text] / M. Mesarovich, D. Mako, Y. Takahara. – New York: Academic, 1970. – 294 p.
13. Rud, Yu. S. Technological equipment of mountain concentrating combines as object of system research [Text] / Yu. S. Rud, V. Yu. Belonozhko, T. S. Belonozhko // Bulletin of the Krivoy Rog Technical University. – 2007. – Issue 19. – P. 93–96.
14. Kolmogorov, A. N. Three approaches to the definition of the concept of «amount of information» [Text] / A. N. Kolmogorov // Problems of Information Transmission. – 1965. – Issue 1 (1). – P. 3–11.
15. Solomonoff, R. A Preliminary Report on a General Theory of Inductive Inference [Text] / R. Solomonoff // Report V-131. – Zator Co., Cambridge, 1960.
16. Solomonoff, R. J. A formal theory of inductive inference. Part I [Text] / R. J. Solomonoff // Information and Control. – 1964. – Vol. 7, Issue 1. – P. 1–22. doi: 10.1016/s0019-9958(64)90223-2
17. Solomonoff, R. J. A formal theory of inductive inference. Part II [Text] / R. J. Solomonoff // Information and Control. – 1964. – Vol. 7, Issue 2. – P. 224–254. doi: 10.1016/s0019-9958(64)90131-7
18. Lyapunov, O. V. On an approach to the synthesis of control systems. Issue 14 [Text] / O. V. Lyapunov // Problems of Cybernetics. – Moscow, 1964. – P. 31–110.
19. Petrov, B. N. Complexity of finite objects and information management theory. Issue 11 [Text] / B. N. Petrov, G. M. Ulanov, S. B. Ul'yanov // Problems of Cybernetics. – Moscow, 1979. – P. 77–147.
20. Nechiporenko, V. I. Structural analysis of systems (efficiency and reliability) [Text] / V. I. Nechiporenko. – Kyiv: Sovetskoe radio, 1977. – 216 p.
21. Cilliers, P. Boundaries, Hierarchies and Networks in Complex Systems [Text] / P. Cilliers // International Journal of Innovation Management. – 2001. – Vol. 5, Issue 2. – P. 135–147. doi: 10.1016/s1363-9196(01)00031-2
22. Goode, H. H. System Engineering: An Introduction to the Design of Large-scale Systems [Text] / H. H. Goode. – McGraw-Hill, 1957. – 551 p.
23. Druzhinin, V. V. Problems of system engineering (problems of the theory of complex systems) [Text] / V. V. Druzhinin, D. S. Kontorov. – Moscow: Sovetskoe radio, 1976. – 296 p.
24. ElMaraghy, H. A model for assessing the layout structural complexity of manufacturing systems [Text] / H. ElMaraghy, T. Al-Geddawy, S. N. Samy, V. Espinoza // Journal of Manufacturing Systems. – 2014. – Vol. 33, Issue 1. – P. 51–64. doi: 10.1016/j.jmsy.2013.05.012
25. Guoliang, F. Operation-based Configuration Complexity Measurement for Manufacturing System [Text] / F. Guoliang, L. Aiping, M. Giovanni, X. Liyun, L. Xuemei // Procedia CIRP. – 2017. – Vol. 63. – P. 645–650. doi: 10.1016/j.procir.2017.03.136
26. Wang, H. Manufacturing complexity in assembly systems with hybrid configurations and its impact on throughput [Text] / H. Wang, S. J. Hu // CIRP Annals. – 2010. – Vol. 59, Issue 1. – P. 53–56. doi: 10.1016/j.cirp.2010.03.007

27. Gu, C. Reliability-oriented Complexity Analysis of Manufacturing Systems Based on Fuzzy Axiomatic Domain Mapping [Text] / C. Gu, Y. He, X. Han // Procedia CIRP. – 2016. – Vol. 53. – P. 130–135. doi: 10.1016/j.procir.2016.06.097
28. Shao, J. Research Progress Analysis of Reliability Design Method Based on Axiomatic Design Theory [Text] / J. Shao, F. Lu, C. Zeng, M. Xu // Procedia CIRP. – 2016. – Vol. 53. – P. 107–112. doi: 10.1016/j.procir.2016.07.027
29. Kim, H. Optimal reliability design of a system with k -out-of- n subsystems considering redundancy strategies [Text] / H. Kim // Reliability Engineering & System Safety. – 2017. – Vol. 167. – P. 572–582. doi: 10.1016/j.ress.2017.07.004
30. Ulesov, A. S. Definition Of amount of information entropy in structure of the technical system by method of the minimum sections [Text] / A. S. Ulesov, D. Y. Karandeev, N. N. Kondrat // Modern problems of science and education. – 2016. – Issue 3. – P. 472–476.
31. Yudin, D. V. Control problems and complexity theory [Text] / D. V. Yudin, A. P. Goryashko // Izvestiya AN SSSR. Technical cybernetics. – 1974. – Issue 3. – P. 34–53.
32. Buslenko, N. P. On the formal description of connections between elements of a complex system [Text] / N. P. Buslenko, A. N. Averkin // Cybernetics. – 1972. – Issue 6. – P. 440.
33. Feizabadi, M. A new model for reliability optimization of series-parallel systems with non-homogeneous components [Text] / M. Feizabadi, A. E. Jahromi // Reliability Engineering & System Safety. – 2017. – Vol. 157. – P. 101–112. doi: 10.1016/j.ress.2016.08.023
34. Rud, Yu. S. Modern equipment for the enrichment of iron ores [Text] / Yu. S. Rud, V. I. Bessarab, L. Z. Ortenberg. – Moscow: Central Research Institute of Information and Technical and Economic Research on Heavy and Transport Engineering, 1982. – 36 p.

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ANALYSIS OF THE FORMATION OF FILAMENT WINDING IN TERMS OF FORCE INTERACTIONS BETWEEN THREADS

M. Nuriyev
Doctor of Technical Sciences, Professor*
F. Veliev
Doctor of Technical Sciences, Professor
Department of Technological Machines
and Equipment of the Industry*
I. Seydaliyev
PhD, Associate Professor*
K. Dadashova
PhD, Senior Lecturer*
G. Jabbarova
Lecturer**
I. Allahverdiyeva
Lecturer**
E-mail: allahverdiyeva.ilhame@inbox.ru
*Department of Standardization and Certification***
Department of Consumer Goods Expertise*
***Azerbaijan State Economic University, (UNEC)
Istiglaliyyat str., 6, Baku, Azerbaijan, AZ 1001

Досліджено процес формування джгутового намотування з точки зору силових взаємодій ниток. Встановлено, що при певних співвідношеннях між частотою обертання бобіни і частотою руху нитководія відбувається укладання ниток на одне й те саме місце і формується джгутове намотування. Для усунення дефектів у вигляді джгутів та супроводжуючих їх хорд запропоновано зменшити до можливого мінімуму відстань від вічка нитководія до точки набігання

Ключові слова: джгутова намотування, хорда, нитководій, дефекти намотування, точка набігання

Исследован процесс формирования жгутовой намотки с точки зрения силовых взаимодействий нитей. Установлено, что при определенных соотношениях между частотой вращения бобины и частотой движения нитеводителя происходит укладка нитей на одно и то же место и формируются жгутовая намотка. Для устранения дефектов в виде жгутов и сопровождающих их хорд предложено уменьшить до возможного минимума расстояние от глазка нитеводителя до точки набегания

Ключевые слова: жгутовая намотка, хорда, нитеводитель, дефекты намотки, точка набегания

1. Introduction

As it is known [1], filament winding is formed when motion frequency of the yarn guide becomes multiple to the rotation frequency of a bale. Because at frictional winding the speed of bale rotation continuously decreases in a certain range with an increase in diameter, the conditions for the formation of filament structures occur periodically.

The quality of bales is defined by the winding structure, which is closely linked to the shape of a bale. The presence