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Specificity of the development of the damage process to network structures of pipeline transportation systems

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Abstract. Introduction. *Industrial pipeline transportation systems are complex, potentially hazardous engineering facilities that ensure the delivery of specified amounts of a target product to consumers. The development of emergencies associated with the transition to the down state of a certain number of pipelines may result in the disconnection of some or all the product consumers from the source. If the system's linear elements transition to the down state in a random order, such a change of the network structure is called a progressive damage. A progressive damage is especially hazardous if, in the course of maintenance activities, a part of the system or a set of process pipelines is disconnected. The* **Aim** *of the work is to identify the change patterns of pipeline system resilience when affected by progressive damage and to develop practical recommendations for ensuring the resilience of such systems in operation and during maintenance operations.* **Methods of research.** *The resilience of systems as the capability to resist progressive damage was evaluated with an indicator that represents the average fraction of pipelines whose transition into the down state causes the disconnection of all consumers from the source of the product. The resilience values were defined by means of computer simulation. The network structure and the nature of the existing intersystem communications were defined using an adjacency matrix.* **Results.** *Damage to a transportation network structure is regarded as a result of a two-stage process. At the stage of target transformation, linear elements are purposefully excluded from a full graph-based structure, bringing the network to a certain initial state. At the second stage, the original structure is transformed according to the mechanism of progressive damage. Such approach allows correctly assessing the changes in the resilience of complex network structures and their ability to resist the development of the processes of damage. The paper sets forth calculated characteristics that allow predicting the behaviour of pipeline networks affected by emergencies. The existence of limit network structures is demonstrated that prove to be very vulnerable to the development of progressive damage.* **Conclusions.** *As the process of targeted transformation goes on, the ability of newly formed network structures to resist the development of progressive damage progressively diminishes. The lowest level of pipeline system resilience against the development of the process of progressive damage can be observed as the structure of the network nears the limit state. When preparing maintenance activities with scheduled exclusion of a number of linear elements from an active pipeline system, the proximity of the newly built network structure to the limit state should be assessed along with the resilience of the restored system to possible development of progressive damage.*

Keywords: *system, pipeline, structure, repairs, damage, resilience.*

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The operation of industrial pipeline transportation systems in nominal operating conditions is associated with the delivery of the required quantities of the target product from the source to individual consumers. Efficiently managing transportation flows and achieving specified process conditions is enabled by the complex network structure and redundant internal communications [1-4]. Such systems are utility facilities, whose condition is to be assessed and that must be repaired accordingly [5-7].

The operation of various pipeline systems [8-10] is associated with the development of degradation processes that define the probability of failure of individual structural elements [11]. Interactions with the environment are diverse [12,13] and create risks one needs to considered and be able to assess [14].

In general, the processes within the systems are multifactor, while their analysis and identification of current state of the network entities is a complex engineering problem [15]. Under such circumstances, emergencies imply the removal of individual pipelines (linear elements) from operation and redistribution of transportation flows within the system.

If the system's linear elements progressively transition to the down state in a random order, such a change of the network structure is called a progressive damage [16].

Progressive damage is a hazardous scenario that transforms an initial transportation network into a set of point elements disconnected from each other. This state of the network entity is characterized by a null-graph, i.e., a graph with no edges.

In practice, achieving such state is impossible, for obvious reasons. Nevertheless, researching the properties of network entities affected by progressive disruption of communications within a system and the reduction of the number of linear elements is of practical interest, while the established process patterns should be taken into account while planning repair and ensuring the stability of the restored pipeline transportation systems.

It is obvious, that resilience as the ability of a system to resist the development of progressive damage depends on the number of the consumers, nodes, linear elements and the nature of the communications between them. Comparing the resilience of different network entities is only possible if they are comparable, i.e., the number of the following is identical:

- end product consumers;
- transportation nodes;
- linear elements.

This means that the failure of even one pipeline does not allow comparing the properties of the original and newly formed system correctly due to differences in the quantitative composition of linear elements.

This circumstance makes it difficult to analyse and evaluate the impact of structural changes on the system's ability to resist the development of progressive damage. In this context, it is required to develop new methods of assessing the properties and behaviour of transportation systems affected by progressive damage.

The technical literature on the behaviour of pipeline systems in emergencies is often insufficient to assess the expected impact of project decisions, which requires further research.

The aim of the work is to identify the change patterns of pipeline system resilience when affected by progressive damage and to develop practical recommendations for ensuring the resilience of such systems in operation and during maintenance operations.

Structural changes in a transportation network as the outcome of a two-stage process

Let us assume that the solution of a certain design problem is associated with the requirement to assess the resilience to progressive damage of the network structures shown in Figure 1. Each of them includes a source of product A, as well as consumers B and C. The first one contains 8, while the second one contains 7 linear elements.

If, in the course of progressive damage, a linear element fails at each point of the system time, a comparison of the resilience of the examined facilities is not valid, as their ranges of system time values do not match. For that reason, the relationship between the number of linear elements in a network and the resilience of a system against progressive damage should be studied on the basis of a different conceptual approach.

Let us examine the matter more in detail. The structure shown in Fig. 1b can be represented as a result of a transformation associated with the exclusion of a linear element from a more complex structure shown in Fig. 1a.

If we consider the process of progressive damage of each of these structures, it will be occurring from different starting positions and be characterized by different values of the resilience indicator.

The resilience indicator $0 \leq F_W \leq 1$ is understood as the average number of pipelines whose random failure causes disconnection of all consumers from the source of the target product [17].

In this context, it should be assumed that the first of the above structures will be more resilient on account of having a larger number of linear elements.

On the other hand, it can be assumed that the structure shown in Fig. 1a is the result of a transformation of a more complex structure shown in Fig. 2. Additionally, the structure of the network entity shown in Fig. 2 can become more complex as the result of development of new connections. If more new connections are added, the resulting complete graph [18], who's each node is connected by edges to all the others, is shown in Fig. 3. Such full graph-based structure is further called basic, while any of the examined network variants is the result of transformation of the same basic structure.

Given the above specificity, it would be convenient to consider the process of damage to a random network

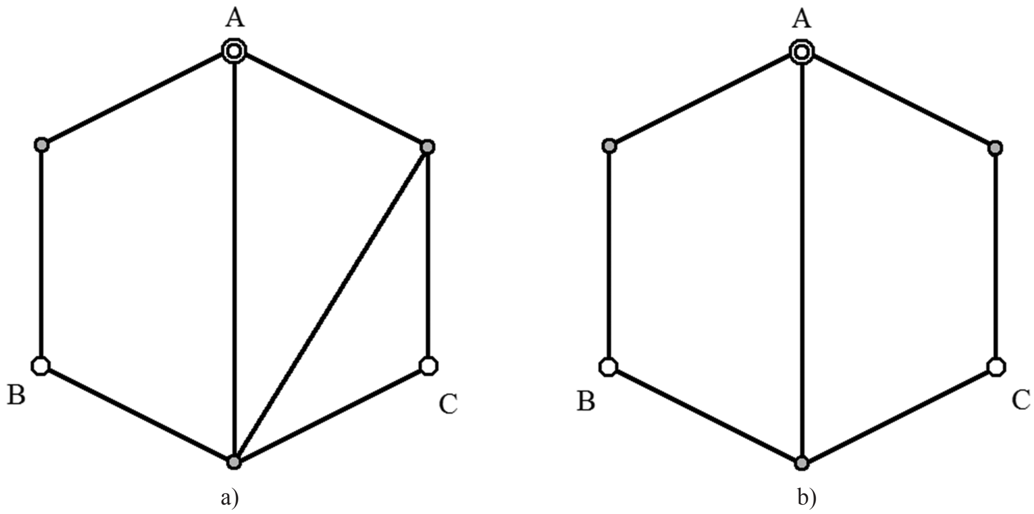

Fig. 1. Network structures of pipeline systems with identical numbers of nodes and consumers comprising 8 (a) and 7 (b) linear elements

structure as proceeding in two stages. At the first stage, the researcher intentionally excludes from the full graph-based network a part of linear elements, thereby bringing the basic structure to the initial one. Since the initial structure is the aim of the transformations, as it is complete, the target transformation is over.

At the second stage of transformation, the disruption of communications between individual nodes of the obtained initial structure occurs randomly by the mechanism of progressive damage.

Since structures with identical numbers of nodes have the same full graph, the range of system time values in the course of the two-step damage process turns out to be the same. This feature of network structures with equal numbers of nodes allows estimating the dynamics of the damage process from a single starting position. A special attention should be paid to the fact that a valid comparison of the resilience of network entities as part of the developed concept of two-stage damage is only possible for identical system time values.

As each of the above stages of damage has its own specific features, they should be examined and analysed separately.

Characteristics and specificity of the target transformation process

Target transformation involves sequential exclusion from the basic full graph-based network structure of a certain set of communications with gradual transition to the initial (target) structure.

The order of disruption of systemic communications in the course of target transformation is defined by the researcher or may be random. The dynamics of this process are characterized by system time t. As individual linear elements are excluded from the basic full graph-based structure, the system time takes on integer values and represents an event counter. Thus, before the onset of progressive damage, the original network structure is considered as the result of the

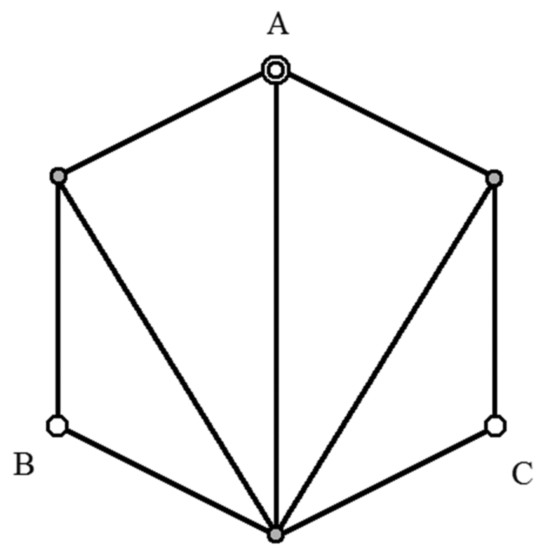

Fig. 2. Structure diagram of a pipeline system

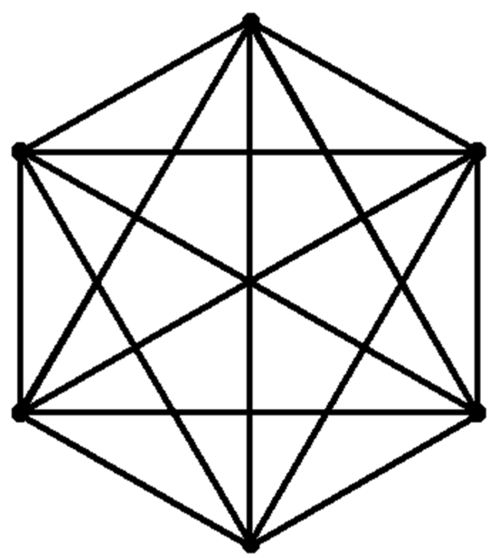

Fig. 3. Complete graph with 6 vertices and 15 edges

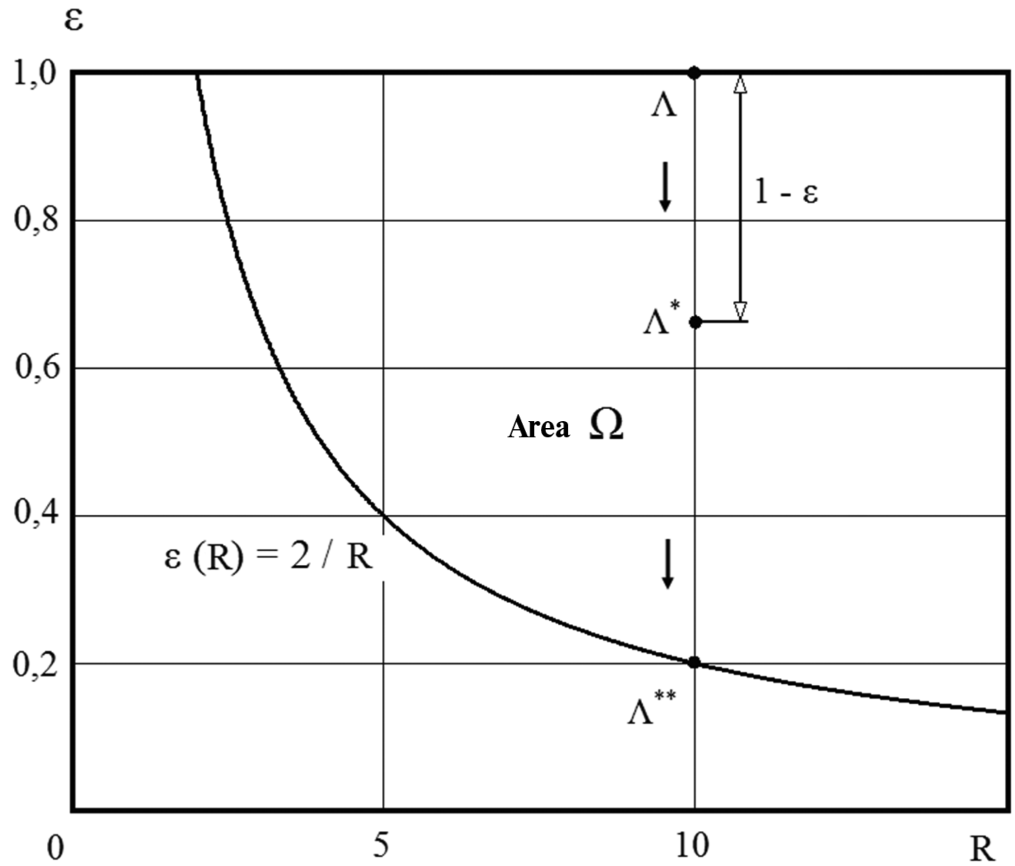

Fig. 4. The displacement of point Λ that characterizes the state of a network entity in the course of target transformation

preceding target transformation of the basic full graph-based object.

It is known that the full graph, at given number of vertices R, has the highest number of edges [19]:

$$Z_m = \frac{R \cdot (R-1)}{2}.$$

Then, the state of the original structure obtained as the result of purposeful removal of a certain number of edges from the full graph will be characterized by the communications completeness coefficient ε. Coefficient ε is the ratio of the number of communications Z between the graph vertices of the original structure to the number of communications in the full graph with the same number of vertices:

$$\varepsilon = \frac{Z}{Z_m} = \frac{2Z}{R \cdot (R-1)} \le 1.$$

Thus, coefficient ε is the share of the total number of communications in the full graph that must be disrupted in order to bring it to a state corresponding to the original network structure. It is obvious that for any full graph, regardless of the number of its vertices, ε = 1.

In the $\varepsilon 0 R$ coordinate system, the process of target transformation of the full graph and its transition into the original structure will correspond to the displacement of point Λ across a series of intermediate steps into position Λ^* (Fig. 4).

Let us also note that the condition of network integrity in the process of target transformation results in restrictions on the lower threshold of values ε. Thus, the relationship between the number of linear elements Z and the number of nodes R for the limit structures with the "line" topology has the form:

$$Z = R - 1. \quad (1)$$

Further disruption of communications between the nodes of such entity will cause its separation into parts, which is unacceptable. Then, the condition of network integrity, taking into account dependence (1), leads to the following restriction:

$$\varepsilon (R) \ge \frac{2}{R}.$$

Accordingly, the range of possible variation of the values of coefficient ε is determined as follows:

$$\frac{2}{R} \le \varepsilon (R) \le 1.$$

Area Ω, for which the combination of parameters ε and R corresponds to the above limitations and possibility of structural integrity upon the completion of the target transformation, is shown in Fig. 4.

In this context, let us consider the following example. Let us suppose that the initial network structure is characterized by the graph shown in Fig. 5a. It contains 12 edges and 8 vertices, while being the result of the target transformation of the full graph that consisting of 8 vertices and 28 edges.

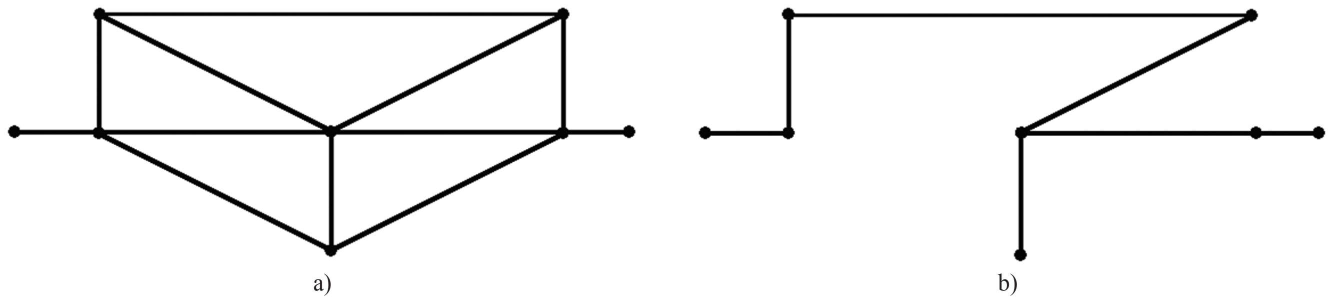

Fig. 5. Graphs that characterize integral network structures before (a) and after deliberate exclusion of 5 linear elements (b)

In the $\varepsilon 0R$ coordinate system (Fig. 6), this complete graph corresponds to point Λ, while the process of the target transformation that results in the formation of the initial network structure is associated with the transition of this point into position Λ^* by the system time t = 16.

If the resulting initial structure with the coefficient ε = 0,43 is later affected by progressive damage, it is obvious that it will be characterized by some resilience to this process. If the target transformation is continued to the point in time t = 21 with transition into the state shown in Fig. 5b, such process' potential would be fully exhausted.

The resulting limit structure is characterized by point Λ^{**} located on the boundary of area Ω (Fig. 6). Further elimination of linear elements from such structure is associated with the division of the network entity into parts or separation of nodes.

Thus, the lower threshold of coefficient $\varepsilon = \frac{2}{R} = 0{,}25$ is the limit value and its attainment in a real-life situation should be considered highly undesirable. This state of a network entity corresponds to the boundary of area Ω and is the maximum allowable in terms of its integrity.

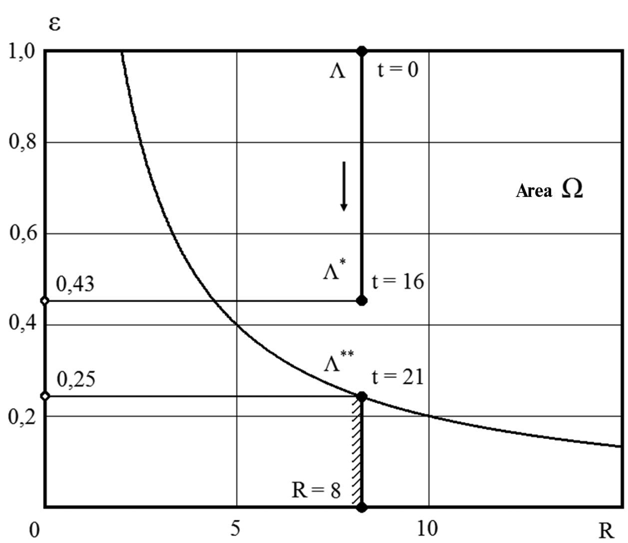

Fig. 6. A graphical representation of the target transformation process

The following formula is to be used for determining the proximity of the current network state to the limit state:

$$\eta = \frac{R\,(R-1) - 2Z}{(R-1)\cdot(R-2)}.$$

Coefficient η changes within the range of $0 \le \eta \le 1$. For a full graph-based structure η=0, and on the boundary of area Ω the value η=1. The range of possible application η should be divided into 3 value ranges according to the data of Table 1.

Thus, the calculation of values η for the analysed network structure helps form a general idea of its ability to resist the development of progressive damage.

Characteristics and specificity of progressive damage process

If we think of the network transformation process as a development of a two-stage process, it should be noted that a full graph-based structure is the most resilient against progressive damage. As linear elements are excluded from such basic structure and the process of target transformation develops, the ability of newly formed structural objects to resist the development of progressive damage decreases.

In this context, let us look into the development of the resilience of the ST0 full graph-based network structure with the source of product *A* and consumers *B*, *C*, *D* occurs (Fig. 7) as it gradually transforms into the limit state with a "line" topology.

Having eliminated 5 linear elements from the system, we will obtain the new ST1 structure outlined in Fig. 8a. For the structure designated ST1, the estimated resilience value is: $F_w = 0.769$. If the target transformation is continued and 4 more linear elements are eliminated from the system, the resulting structure designated ST2 will be as shown in Fig. 8b. Its calculated characteristics are given in Table 2.

Table 1. Verbal scale of network structure properties

Range of coefficient values η	$0 \le \eta < 0{,}5$	$0{,}5 \le \eta < 0{,}75$	$0{,}75 \le \eta \le 1$
Verbal scale of network structure properties	High resilience to progressive damage is ensured	The ability to ensure resilience to progressive damage is not high	The ability to ensure resilience to progressive damage is limited or very low

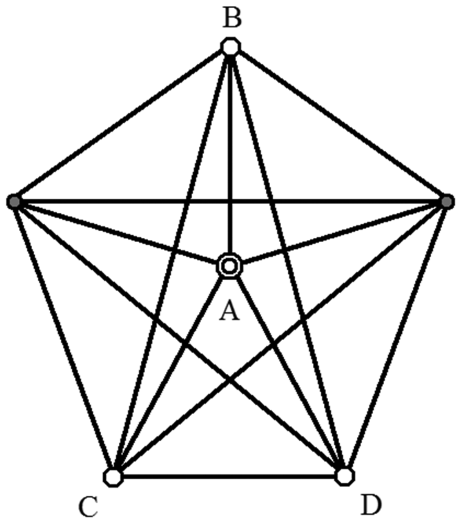

Fig. 7. Full graph-based structure ST0 with source A and consumers B, C, D

The elimination of two more linear elements results in the ST3 structure with the “ring” topology (Fig. 8c), after which only one linear element can be removed as part of target transformation (Fig. 8d).

As the result, the limit structure ST4 with the “line” topology is formed. The calculated characteristics of the above network structures are also shown in Table 2. It can be observed that the most significant decrease in the values of the resilience indicator in the process of target transformation is within the range $\eta = 0.7 \ldots 1$, i.e., as the network structure approaches its limit state.

The following specificity should be noted. For each of the examined structures, there are some variations due to possible changes in the mutual arrangement of the consumer nodes under the condition $\eta = \text{const}$.

For example, variations of the ST3 and ST4 structures can be related to a relocation of consumer node *C* (Fig. 9) with the value of η remaining unchanged. The interval estimates of the resilience values shown in Fig. 10 were obtained on the assumption of calculation error and the presence of some structural variations for fixed values of η.

The findings suggest that redundant intersystem connections have a positive effect on the resilience of pipeline systems to progressive damage, while the nature of such effect is non-linear. The most positive effect of the inclusion of additional connections into a system is observed if the network structure is close to the limit.

Conclusions

1. As the process of targeted transformation progresses, the ability of newly formed network structures to resist

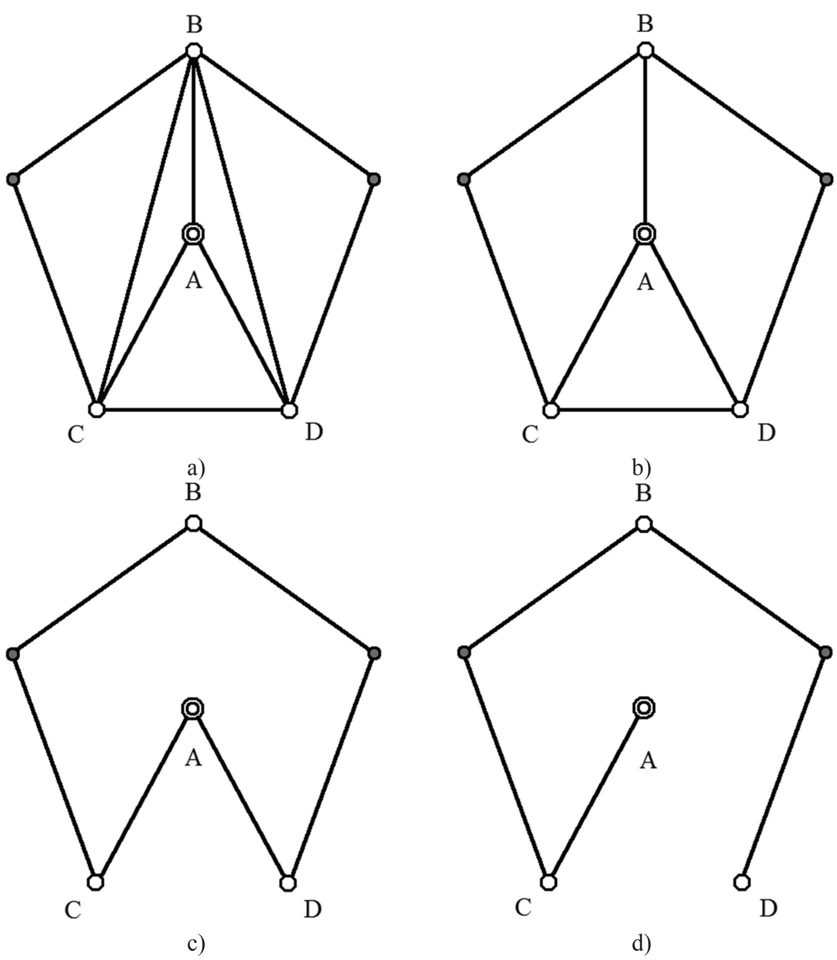

Fig. 8. Network structures designated ST1 (a), ST2 (b), ST3 (c), ST4 (d)

Table 2. Characteristics of network structures

Network structure designation	Characteristics of structures and process of targeted transformation						Note
	t	R	Z	ε	η	F_w	
ST0	0	6	15	1.0	0	0.800	The structure is based on a whole graph
ST1	5	6	10	0.667	0.5	0.769	
ST2	7	6	8	0.533	0.7	0.720	
ST3	9	6	6	0.4	0.9	0.581	
ST4	10	6	5	0.333	1	0.377	Limit structure composition

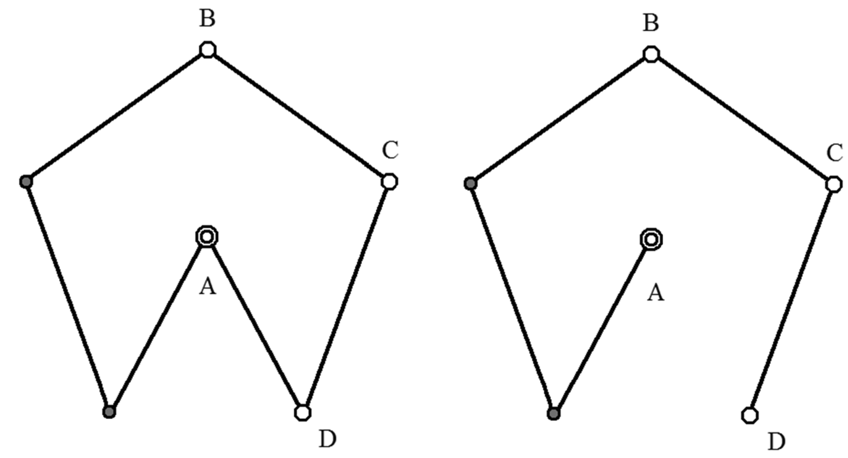

Fig. 9. Variation of the ST3 (a) and ST4 (b) structures associated with the repositioning of consumer node C

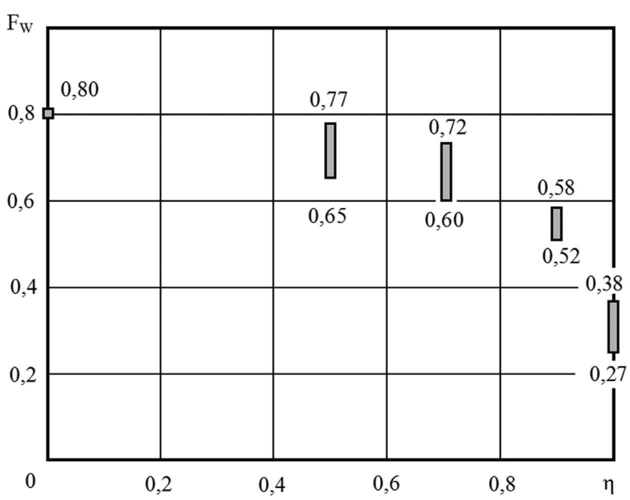

Fig. 10. Interval estimates of FW values for a set of comparable structures with fixed η values

the development of the process of progressive damage is continually diminished.

2. The lowest level of pipeline system resilience against the development of progressive damage can be observed as the structure of the network nears the limit state.

3. When carrying out maintenance activities associated with the exclusion of a number of linear elements from an active pipeline system, the proximity of the newly built network structure to the limit state should be assessed along with the resilience of the restored system to possible development of the process of progressive damage.

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The author's contribution

The author suggested the concept of two-stage damage to the network structure of a pipeline transportation system that allows estimating the changes in the durability of the repaired systems and the possible consequences of structural changes associated with repair activities. The required calculation dependencies were obtained that allow predicting the behaviour of such systems in emergency situations.

Conflict of interests

The author declares the absence of a conflict of interests.