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Ensuring resilience of pipeline transportation systems to damage to network structure elements

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The **Aim** *of the paper is to study the patterns of development of progressing damage affecting network structure elements of pipeline systems and to develop recommendations for ensuring the resilience of such engineering facilities. The progressing damage process is understood as the procedure of transition of linear elements (pipelines) of a system into the state of non-operability occurring in a random sequence. The capability of a system to resist progressing damage was evaluated with the resilience indicator F_w that represents the average fraction whose transition to the state of non-operability causes the disconnection of all consumers from the source of the product.* **Methods of research.** *The values of $0 < F_w < 1$ were identified by means of computer simulation. While performing a structural analysis of the systems the set of all linear elements was considered to be composed of five subsets G1, ..., G5 that connect point elements of various types.* **Results.** *It was established that elements belonging to different subsets have different effects on the system's resilience to progressing damage. The highest effect is created by the elements of subsets G1 and G2. These elements form the "core" of the network facility. The resilience to damage is least affected by the elements of subsets G4 and G5. They may be considered as a "remote periphery" of the network structure. The remote periphery interacts with the core by means of the elements belonging to subset G3. That is the "close periphery" that ensures communication between the core and the remote periphery. The effect of subset G3 elements on the resilience to damage turns out to be lower than that of the elements belonging to the core, yet higher than that of the elements of the remote periphery. Thus, the design of a pipeline system may be represented as a layered object. The core includes linear elements that interconnect the consumer and the source of the product. The higher the number of connections in the core, the higher the resilience of the network structure is.* **Conclusions.** *It was established that the resilience of network structures to progressing damage depends on their composition, while the set of all pipelines can be divided into five subsets of which the elements have different effects on the whole system's resilience. The network structure of a pipeline system may be represented as a layered object with a core, close and remote periphery. It was established that the resilience to damage largely depends on the quantitative composition and the nature of the interaction between the elements of different layers. "Tree"-type network elements are characterized by a low level of resilience to progressing damage. The resilience of such facilities can be improved by forming a core and introduction of additional linear elements into the system's composition.*

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

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Introduction. Pipeline transportation systems are used in a number of the sectors of economy and industry. They are part of the energy, engineering, metal, chemical, oil and gas industries. The operational properties of such complex engineering facilities depend on their structure that is made at the design stage subject to the expected characteristics of the whole system. While evaluating the probability of damage to the network structures of pipeline systems as a result of transition in the state of non-operability of individual linear elements, it should be noted that such processes may be due both to the development of internal processes within the system, and external reasons. Normally, when emergency situations arise and develop, the process of progressive transition of a number of pipelines into the state of non-operability can be observed. The process may be accompanied by the disconnection of some or all consumers from the source of the main product.

The process of further progressive transition of the system's linear elements (pipelines) into the state of non-operability in random order is called progressing damage [1]. The ability of a pipeline system to resist progressing damage primarily depends on its network structure and is characterized by such concept as resilience.

A structure's resilience to the development of progressing damage is evaluated in terms of the resilience indicator *Fw* that is the average fraction of the total number of linear elements (pipelines), whose transition into the state of non-operability causes the interruption of the delivery of the main product to all consumers.

The **Aim** of this paper is to study the patterns of development of progressing damage affecting network structure elements of pipeline systems and to develop recommendations for ensuring the resilience of such engineering facilities.

Resilience of pipeline transportation systems to damage to network structure elements

It does not appear to be possible to analytically identify the values of the resilience indicator for the given network structure. That is due to the requirement to generate a random sequence of damage to linear elements and evaluate the results of each fact of damage with subsequent generation of a database to enable the identification of F_w. At the same time, today's methods of mathematical simulations are best suited to such tasks [2].

Thus, in the process of software development in MathCAD the marked-out graph of the initial network structure was defined with a connectivity matrix [3]. Each act of graph edge damage that corresponds to transition of the system's individual pipeline into the state of non-operability was random in accordance with the MathCAD computing capabilities. The consequences of damage to network structure elements were evaluated subject to the existing connections between the source and the consumers of the product using reachability matrices [5].

The resulting set of reachability matrices was used to identify the percentage of linear elements of which the transition into the state of non-operability causes complete disconnection of all consumers from the source of the main product.

The above calculation algorithm was repeated multiple times in order to make a database required for the identification of the statistical characteristics of the random value $\boldsymbol{F_w}$.

In general, the pipelines of the transportation system connect various point objects, while the set of all linear elements can be divided into 5 subsets of which the characteristics are given in Table 1. The research findings show that elements belonging to different subsets have different effects on a working system's resilience to progressing damage.

Thus, the quantitative composition of the subsets of the network structure shown in Fig. 1 is given in Table 2. It also shows the values of resilience indicator F_w identified by means of computer simulation. In the course of the research the initial network structure *SK* (Fig. 1) was transformed in such a way as to one by one exclude the elements belonging to subsets *G*1, …, *G*5. For the network objects *SK*1, …, *SK*5 that appear in the process the values of F_w were identified (Table 2).

The findings allow concluding that a network structure's resilience to progressing damage is most affected by the elements of subset *G*1. The elements of the other subsets have a lesser effect that progressively diminishes from *G*2 to *G*3 and further from *G*4 to *G*5.

Table 1. Designation of subsets of linear elements within the network structure

Designation of subsets of linear elements	Characteristics of point element connections	Conventional representation of the elements of corresponding subsets	Number of subset elements within the network structure
*G*1	Source – consumer		g_1
*G*2	Consumer – consumer		g_2
*G*3	Consumer – hub		g_3
*G*4	Hub – hub		g_4
*G*5	Source – hub		g_5

The simulation results show that the identified trends are also observed in more complex structural facilities with a large number of consumers and structural elements.

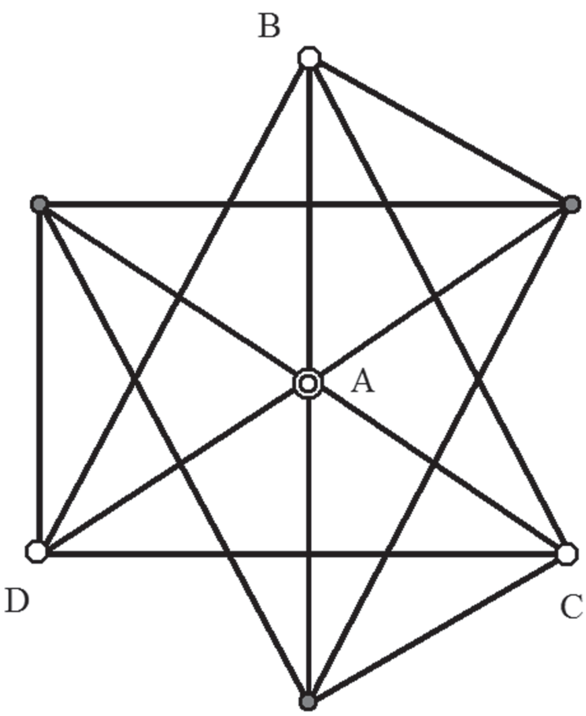

Figure 1. Structure of a system with conventional designation SK

In general, the analysis of the resulting data allows establishing the presence of the following patterns.

1. The network structure's resilience to damage is most affected by elements of subsets *G1* and *G2*. These elements form the "core" of the network facility.

2. The resilience to damage is least affected by the elements of subsets *G4* and *G5*. They may be considered as a "remote periphery" of the network structure.

3. The remote periphery interacts with the core by means of the elements belonging to subset *G*3. Their sum can be considered the "close periphery" that ensures communication between the core and the remote periphery. The effect of subset *G*3 elements on the resilience to damage turns out to be lower than that of the elements belonging to the core, yet higher than that of the elements of the remote periphery.

The findings allow concluding that, in general, the structure of a pipeline system may be represented as a layered object shown in Fig. 2.

The core includes linear elements that interconnect the consumer and the source of the product. The higher the number of elements in the core the higher is the resilience of the network structure.

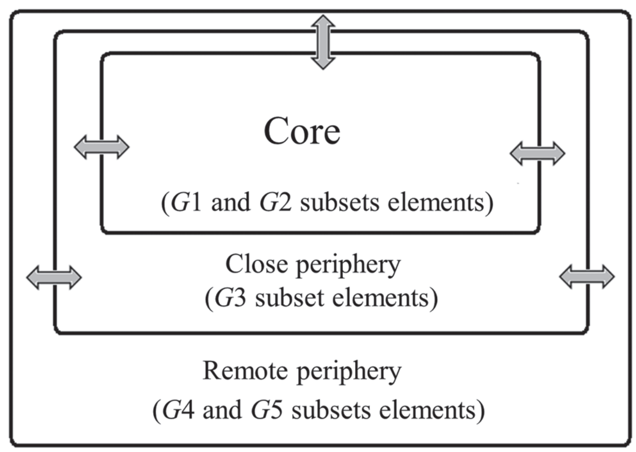

Figure 2. Diagram of a three-layer structural object

Resilience to progressing damage of network structures based on acyclic graphs

In many cases, the design and manufacture of pipeline transportation systems is associated with the requirement to distribute and deliver the main product to a large number of various consumers. The consumers, in turn, are grouped in a certain way in accordance with the adopted process flow cart. For example, an enterprise-level hub delivers specified quantities of main product to consumers in individual shops. In each shop, the product is distributed among aisles, areas and individual workstations (groups of production equipment).

Possible distribution of main product and diagram of its delivery to individual consumers distributed over different production sites is shown in Fig. 3. Such network structures are described with acyclic graphs also called "trees" [6].

The distinctive feature of such structures is that connection of any graph nodes is only possible in one way and only via specific edges. In other words, there is only one way from one node to another.

The use of levels in the description of "trees" allows establishing a hierarchy of individual elements and evalu-

Table 2. Model prediction of the progressing damage process for various network structures

Structure designation	Network structure composition					Resilience indicator F_w
	g_1	g_2	g_3	g_4	g_5	
*SK*1	0	3	3	3	3	0.586±0.006
*SK*2	3	0	3	3	3	0.660±0.006
*SK*3	3	3	0	3	3	0.677±0.008
*SK*4	3	3	3	0	3	0.741±0.005
*SK*5	3	3	3	3	0	0.748±0.007

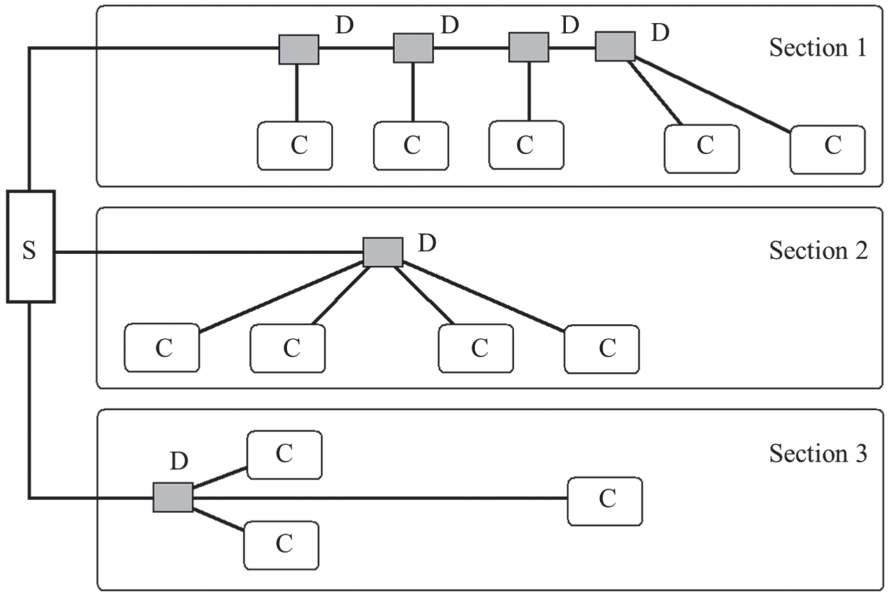

Figure 3. Diagram of product delivery from the source (S) through distributors (D) to individual consumers (C)

ating their role in the process of main product delivery to consumers.

While considering a “tree”-type facility in terms of potential development of progressing damage process it can be argued that such structure is quite vulnerable. The elimination of any linear element from its structure will cause a division of the network facility into separate parts.

In practice, such situations are quite dangerous, as any event involving the transition of linear elements into the state on non-operability will be accompanied by the disconnection of at least one consumer from the source. That means that “tree”-type structures are characterized by a low level of resilience to progressing damage.

In this context it is required to evaluate the resilience to progressing damage of network structures based on acyclic graphs, as well as establish the feasibility and efficiency of various measures aimed at improving the value F_w.

Let us examine the properties of the network structure of a tree-based pipeline transportation system shown in Figure 4. This structure is characterized by the following composition: $g_1 = 0$; $g_2 = 0$; $g_3 = 12$; $g_4 = 6$; $g_5 = 3$.

Its representation in the form of a layered facility is shown in Figure 5. As it can be seen, this structure is completely devoid of core elements. For that reason high values of resilience to progressing damage should not be expected from such facilities.

Given the above, the exclusion of one or more linear elements from the facility’s composition causes a significant reduction of the whole system’s operational capabilities. Additionally, due to the hierarchic nature of the connections between individual units the highest hazard is posed by damage to the elements belonging to the subset from *G*5 to *G*4.

Simulation of the process of progressing damage for the “tree”-type structure under consideration allows identifying

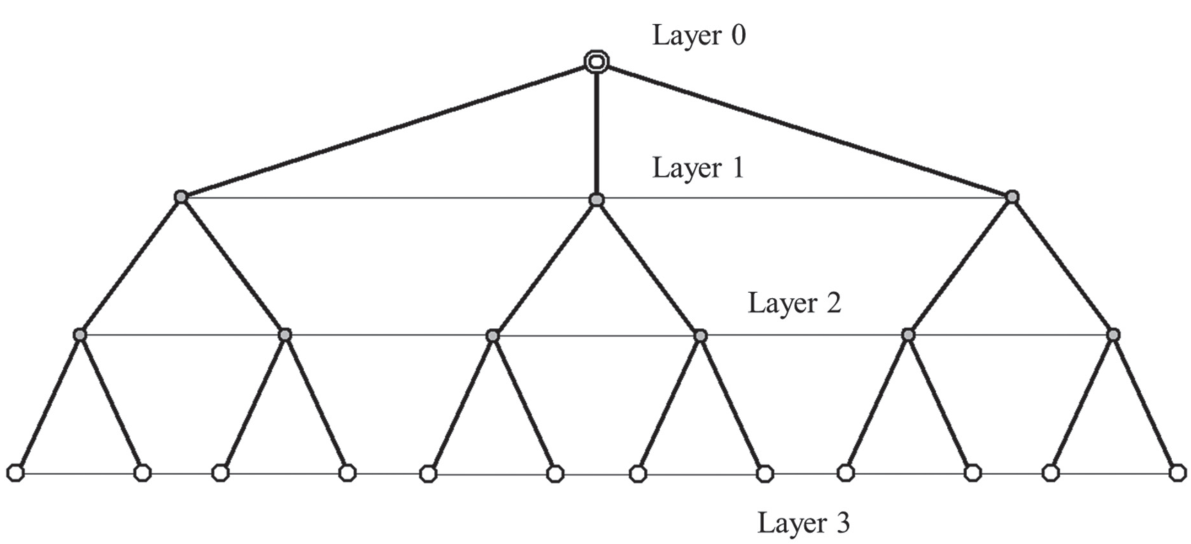

Figure 4. Diagram of a “tree”-based network structure

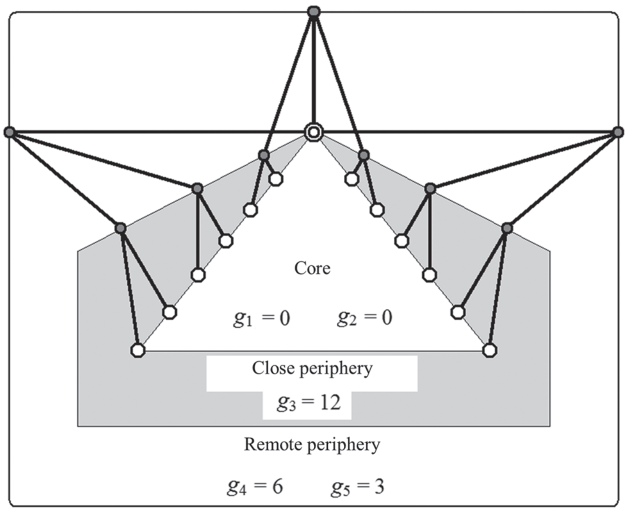

Figure 5. Representation of network structure in the form of a layered facility

the value: $F_w = 0.291$. The value F_w can be most efficiently increased by shaping a core of the network object.

In practice, that means the need for additional linear elements between the source and each consumer. However, if the number of consumers of the main product is large this solution is very difficult to implement.

Additionally, connections can be established between pairs of consumer units. From the practical point of view, the solution involving connections between individual consumers is the most acceptable. That entails the requirement to add to the structure shown in Figure 4 11 elements of subset *G*2 that interconnect consumers at Layer 3. The simulation of progressing damage of such facility allows obtaining the following value of the resilience indicator: $F_w = 0.447$.

As it can be seen, the use of the simplest method of increasing the value F_w for a "tree"-type structure is quite efficient and increases the resilience value by 54%.

If this growth is considered insufficient, the value F_w can be increased even further by means of the above measures.

However, it must be taken into consideration that the creation of new connections will be associated with both the growth of the number of linear elements and the overall complexity of the whole pipeline system. For that reason the adoption of the final solution in any case is a tradeoff.

Now, let us consider the structural diagram of a pipeline system with the "bus" topology (Fig. 6) that is a special case of the acyclic graph. Such network facility can be represented as a layered one with a "tree"-type structure and the following composition characteristics: $g_1 = 0$; $g_2 = 0$; $g_3 = 5$; $g_4 = 3$; $g_5 = 1$.

As it can be seen, the facility under consideration is devoid of core elements. That is the reason of low values of resilience to progressing damage.

Thus, the simulation of damage resulted in the following value of the resilience indicator: $F_w = 0.259$. That means that the delivery of the main product to all consumers will be interrupted if about 26% of all the system's pipelines are in

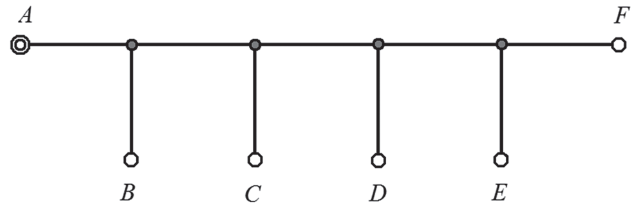

Figure 6. System elements connection in accordance with the "bus" topology

the state of non-operability.

One of the ways of improving the resilience to progressing damage is to connect all consumers of the main product with linear elements as shown in Fig. 7.

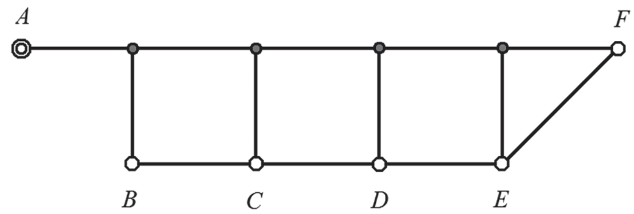

Figure 7. Diagram of the network structure with interconnected main product consumers

Simulation of the progressing damage process for this structure yields the value $F_w = 0.369$ which is 42% higher than the previously identified value for the "bus"-type network structure.

Other solutions aimed at improving the value F_w can be chosen if required. Additionally, all previously made recommendations regarding the resilience of structures based on acyclic graphs still hold as regards network structures with "bus"-type topology.

Conclusions

1. It was established that the resilience of network structures of pipeline transportation systems to progressing damage depends on their composition, while the set of all pipelines can be conventionally divided into 5 subsets of which the elements have different effects on the whole system's resilience to damage.

2. In general, the network structure of a pipeline system may be represented as a layered object with a core, close and remote periphery. It was established that the resilience to damage largely depends on the quantitative composition and possible interaction between the elements of different layers.

3. It was shown that "tree"-type network structures are characterized by a low level of resilience to progressing damage. The resilience of such facilities can be improved by forming a core and introducing additional linear elements into the system's composition.

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